Volume 21 JULY, 1937 Number 7

BULLETIN
of the
American Association *of* Petroleum Geologists

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BULLETIN

of the

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

OFFICE OF PUBLICATION, 608 WRIGHT BUILDING, TULSA, OKLAHOMA

THE BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS is published by the Association on the 15th of each month. Editorial and publication office, 608 Wright Building, Tulsa, Oklahoma, Post Office Box 1852, Cable address, AAPGEOL.

THE SUBSCRIPTION PRICE to non-members of the Association is $15.00 per year (separate numbers $1.50) prepaid to addresses in the United States. For addresses outside the United States, an additional charge of $0.40 is made on each subscription to cover extra wrapping and handling.

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German agent: Max Weg, Königstrasse 3, Leipzig, Germany.

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BOX 1852

TULSA, OKLAHOMA

Entered as second-class matter at the Post Office of Tulsa, Oklahoma, and at the Post Office at Menasha, Wisconsin, under the Act of March 3, 1879. Acceptance for mailing at special rate of postage provided for in section 1103, Act of October 3, 1917, authorized March 9, 1923.

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, INC.

(Organized at Tulsa, Oklahoma, February 10, 1917, as the Southwestern Association of Petroleum Geologists. Present name adopted, February 16, 1918. Incorporated in Colorado, April 23, 1924. Domesticated in Oklahoma, February 9, 1925.)

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The Point of the Guadalupes from a position three miles due south, showing the Guadalupe Escarpment (west-facing eroded fault scarp) and the partially eroded eastern reef front. The smoothly rounded hills in the foreground are composed of Bone Spring limestone (BS). Above and behind them are the Delaware Mountain sandstones (D) with resistant limestone and sandstone beds capping the fluted salients. Surmounting all rises the magnificent buttress of Capitan limestone at the Point. On the east side of the Point, Capitan reef beds (C) may be seen descending to meet the more horizontal Delaware Mountain sandstones (D) with which they interfinger.

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JULY, 1937

THE PERMIAN FORMATIONS OF THE PECOS VALLEY OF NEW MEXICO AND TEXAS[1]

WALTER B. LANG[2]
Washington, D. C.

ABSTRACT

Abrupt changes in lithologic character of the sediments as they pass from the subsidiary Delaware basin into the main Permian basin have made difficult the correlation of the Permian strata in the Pecos Valley. These sediments are here divided into three regional zones and an attempt is made to clarify by diagram their lateral relationships and to explain briefly the essential causes for their lithologic variations. A full section of Permian strata is shown and tentative correlations are proposed with formations of northern Texas and Oklahoma. The southern Permian basin presents the thickest and most continuous record of Permian sediments in the United States. Structural movement is suggested as the primary cause for reef development. The composition of a sediment commonly determines the color; the color of the Permian sediments is considered to be an index of the degree of salinity of the water in which they were deposited and to indicate their relative position in the basin at the time of deposition. The Permian sands are believed to have come from Llanoria and Appalachia.

PART I

INTRODUCTION

Since Murchison's historic investigation of the rocks of Russia which led him across the vast expanse of redbeds lying west of the Ural Mountains and resulted in the recognition of a new system[3] in 1841, problems concerning this assemblage of rocks have been numerous and controversial. In England and Wales Murchison and others had previously observed unfossiliferous red sandstones, conglomerates, and the Magnesian limestone lying above the Coal measures. In Germany the Zechstein, in Belgium the Penéen conglomerate,

[1] Presented before the Association at Tulsa, March 18, 1936; the West Texas Geological Society at Midland, Texas, April 4, 1936; the Geological Society of New Mexico at Carlsbad, New Mexico, May 2, 1936. Manuscript received, April 14, 1937. Published by permission of the director of the United States Geological Survey.

[2] United States Geological Survey.

[3] Murchison, Verneuil, and Keyserling, *The Geology of Russia in Europe and the Ural Mountains*, Vol. I (1845), pp. 137–41.

and in France a red sandstone had yielded few fossils or none at all. The formations that Murchison found were only partial representatives of the sequence of rocks that spread over more than one-third of Russia and to which he gave the geographic name Permian from the ancient kingdom of Permia.

It was not until 1858 that Permian rocks were known to exist as such in America. G. G. Shumard, who was acting as geologist with Capt. John Pope's expedition in western Texas and New Mexico, collected fossils during his reconnaissance[4] west of the Pecos River in 1855. These were subsequently submitted to his brother, B. F. Shumard, for examination, who reported[5] the results of his findings before the St. Louis Academy of Sciences and announced that the fossils were from Permian strata.

The Permian strata of the Pecos Valley are of more than usual interest because of the presence of geologic features not common to sedimentary deposits. Here enormous limestone reefs grew under conditions that caused anomalous variations in sedimentation. These marked changes in the lithologic and biologic character of the sediments have made correlation difficult. It is the purpose of this paper to propose a correlation of the Permian strata of the Pecos Valley and to provide a system of nomenclature that should facilitate future work in the area.

The writer has gained a perspective of southern Permian basin geology while in charge of potash investigations for the United States Geological Survey covering a period of more than a decade. This preliminary reconnaissance with its voluminous collection of sample data, the other urgent requirements of the investigation and the following five-year period of core drilling of the Salado halite, left little opportunity for other than cursory examinations of the extensive outcrops of Permian rocks along the margins of the basin. These examinations were sufficient only for the immediate economic problem at hand.

The outcrops along the borders of the basin reveal the rocks that lie deeply buried beneath the extensive central basin area, and they are there covered by many kinds of surficial deposits of different ages. The Permian deposits of the basin contain the economic products, oil and potash, for the discovery and development of which the

[4] G. G. Shumard, *A Partial Report on the Geology of Western Texas*, Austin State Printing Office (1886), Chap. V, pp. 88–96.

[5] B. F. Shumard, "Notice of New Fossils from the Permian Strata of New Mexico and Texas," *Trans. St. Louis Acad. Sci.* (March 8, 1858).
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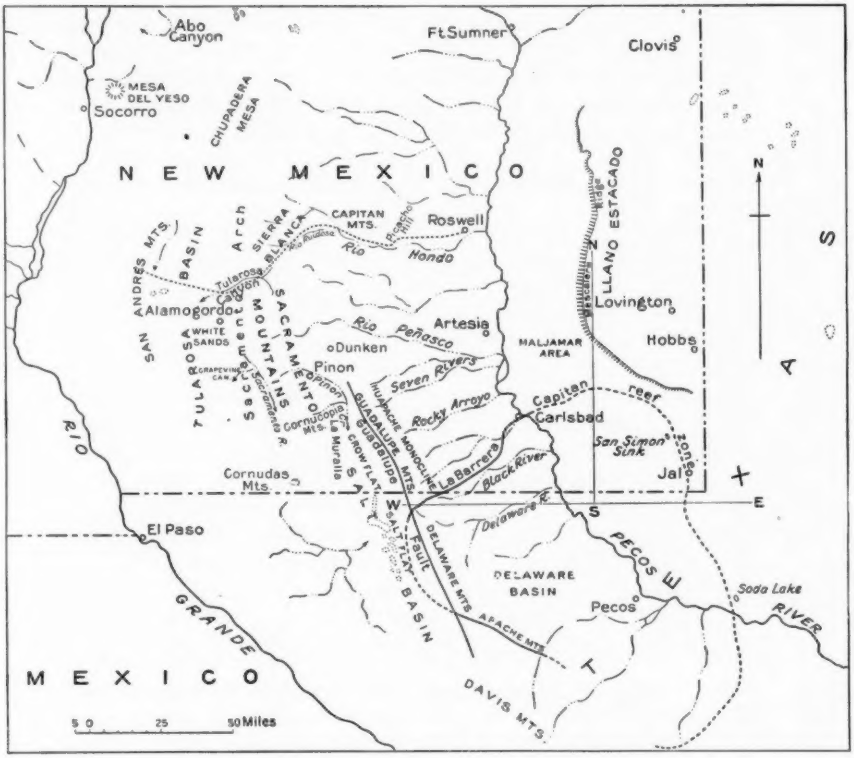


FIG. 1.—Key map of the Pecos Valley area of New Mexico and Texas, on which are shown the Delaware basin and related surface and subsurface features. Localities from which some names of formations are derived are shown. Exposed parts of the Capitan reef are shown by a solid line. Lines N-S and W-E indicate relative positions of the cross sections.

study of the subsurface geology was of primary importance. But, outcrops of Permian rocks on opposite sides of the basin do not agree in color or lithology. From an interpretation of well records a more and more definite conception of the stratigraphy between the outcrop areas has evolved. This has come about only through the combined efforts of a host of geologists and a liberal spirit of coöperation. To the many field geologists engaged in the development of the petroleum industry whom it has been the pleasure of the writer to know, he expresses his debt of gratitude for their many helpful kindnesses. In addition, he is particularly indebted to P. B. King and to H. D. Miser for their generous criticisms and suggestions.

HISTORY OF GEOLOGICAL EXPLORATION

Though the Spanish explorers ventured into the region of the Permian basin in the 16th century, geological interest was not aroused until the period of the gold rush to California in 1849, which created a demand for information concerning stage-coach routes. Pope's investigation for water in 1855, in which Shumard assisted as geologist,[6] is probably the first attempt to apply the geology of the area to practical purpose. Later came the railroad surveys, mineral surveys, studies in hydrology, and finally the stimulus in the search for and production of oil and potash. The early publications appeared at irregular intervals during a period of 75 years—those of the Shumards, Hill, Tarr, Girty, Richardson, Udden, Beede,[7] and others—but since the establishment of crude oil production in West Texas in 1925, many reports have been written giving new observations and interpretations based on subsurface as well as surface geology. These more recent reports have sharpened the hitherto nebulous picture of Permian basin geology and disclosed the presence of the Delaware

[6] G. G. Shumard, *A Partial Report on the Geology of Western Texas, etc.*, Austin State Printing Office (1886).

[7] G. G. Shumard, *op. cit.*

B. F. Shumard, "Notice of New Fossils from the Permian Strata of New Mexico and Texas, etc." *Trans. St. Louis Acad. Sci., 1858*, Vol. 2 (1860), pp. 290–97.

R. T. Hill, "Physical Geography of the Texas Region," *U.S. Geol. Survey Topographical Atlas*, Folio 3 (1900).

R. S. Tarr, "Reconnaissance of the Guadalupe Mountains," *Geol. Survey of Texas Bull. 3* (1892).

G. H. Girty, "The Guadalupian Fauna," *U. S. Geol. Survey Prof. Paper 58* (1908).

G. B. Richardson, "Report of the Reconnaissance in Trans-Pecos Texas, North of the T. and P. Ry.," *Univ. of Texas Mineral Survey Bull. 9* (1904).

J. A. Udden, "Notes on the Geology of the Glass Mountains," *Univ. of Texas, 1753* (1917), pp. 3–59; "Laminated Anhydrite in Texas," *Bull. Geol. Soc. America*, Vol. 35 (1924), pp. 347–54.

J. W. Beede, "The Correlation of the Guadalupian and Kansas Sections," *Amer. Jour. Sci.*, 4th ser., Vol. 30 (1910), pp. 131–40.

basin, a subsidiary basin that was of major importance in its effect upon sedimentation.

PERMIAN PROVINCES AND BASINS IN THE UNITED STATES

The Permian deposits of the United States, except for certain minor occurrences, may for convenience be considered as occupying two major provinces: the Rocky Mountain and Plateau areas and the Mid-Continent area. The dividing line between these two major provinces is the trace of the Rocky Mountain front and the east front of the mountains farther south. Scattered minor outcrops of the Permian occur both in the Atlantic (Dunkard group of West Virginia) and in the Pacific coast states. The deposits of the Mid-Continent constitute a large area that is generally referred to as the Permian basin. This basin may again be divided into two parts, the northern Permian basin and the southern Permian basin. The southern Permian basin is defined as the area south of the Amarillo-Wichita uplift, west of the Bend arch, north of the Marathon folded belt, and east of the Sacramento Mountains. Within this southern division are now recognized two distinct depressions—the Midland and Delaware basins.

GENERAL GEOGRAPHY AND GEOLOGY OF THE SOUTHERN PERMIAN BASIN

The great bulk of the Permian deposits of the southern Permian basin is concealed from view by Triassic, Cretaceous, Tertiary, and Quaternary deposits. On the east where these Permian beds crop out they are largely represented by redbeds, and on the west by limestones and sandstones of a different color. The changes in lithology and color of these rocks occur beneath an extensive mask of cover rock and have been a source of difficulty in correlation. The Permian limestones, which are fossiliferous and therefore offer more definite evidence for correlation, are best exposed in the Guadalupe, Delaware, and Sacramento mountains which border the basin on the west. A study of these exposures serves as an aid to the interpretation of subsurface geology.

THE GUADALUPE MOUNTAINS

The Guadalupe Mountains form a cuesta and constitute the highland area west of Carlsbad, New Mexico, which gradually rises from an altitude of 3,100 feet in the Pecos Valley to 8,751 feet, 60 miles farther west, where they are cut off by a series of faults. A portion of this cuesta which stands higher than the rest has the form of a V. The

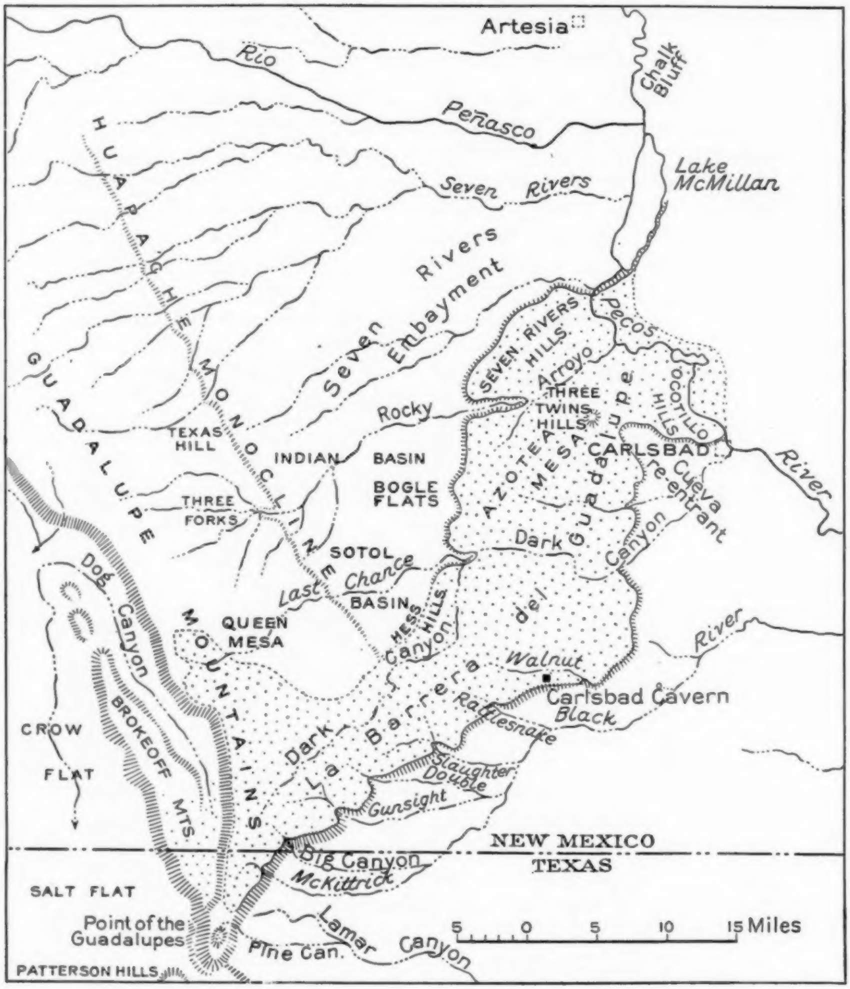


FIG. 2.—Map of the exposed portion of the Capitan reef. Stippled area represents the outcrop of Carlsbad limestone which blankets the Capitan limestone beneath it. The Capitan limestone is to be seen only in the canyons and along the reef front west of Rattlesnake Canyon, in the Guadalupe scarp, and in the Patterson Hills. Localities from which formation names have been taken are shown.

left side or western limb of the V consists of the Guadalupe Mountains proper, which constitute a northwest-southeast trending tableland and which form the highest portion of the Guadalupe cuesta. This part of the cuesta is bordered on the west by faults and on the east by a monocline (1,100+ feet high) to which is given the name Huapache monoclinal fold (Fig. 2 and Fig. 12). The eastern limb of the V has a different origin and relation to the stratigraphy of the area. It is composed of reef limestones laid down on the margin of the Delaware basin and it is here proposed to call it La Barrera del Guadalupe (the barrier of the Guadalupes). The northeastern portion of the Barrera is cut through by two deep canyons, Rocky Arroyo and Dark Canyon. Between these two canyons is a tableland which is here named Azotea Mesa, and the northeastern end of the Barrera north of Rocky Arroyo is commonly known as the Seven Rivers Hills. The trend of the front of the Barrera is sinuous. Fifteen miles southwest of Carlsbad an abrupt change in the trend (Fig. 2) occurs, forming the Cueva re-entrant, which is the most pronounced deviation in trend to be seen along the reef front, and suggests the possible occurrence of similar variations in the subsurface geology. The Guadalupe Mountains proper and the Barrera are composed of resistant limestones but between them there once lay less resistant sandstones, anhydrites, and redbeds, and their removal by erosion has formed the Seven Rivers embayment. The southern part of this embayment is drained by two systems: Rocky Arroyo, which carries off all water falling within Indian Basin and the drainage area of Three Forks, and the Last Chance-Wagontire-Trimble Canyon system, which drains the waters of Sotol Basin into Dark Canyon. Sotol Basin lies at the southern tip of the embayment between the Hess Hills and the Huapache monoclinal fold.

Origin of nomenclature.—The name Guadalupe is probably of Moorish derivation. Columbus, in 1493, named an island of the West Indies Guadalupe after the Spanish Madonna. The Rio de Guadalupe of Texas received its name during subsequent explorations of the Gulf Coast about 1519 or shortly thereafter. The earliest record of its appearance on a map that has come to the attention of the writer is that of the Ulpius Globe[8] of 1542. Subsequently the highland watershed of Rio de Guadalupe, now known as the Edwards Plateau, was called the Guadalupe Mountains. Later maps show a shift of the name to a range of mountains in New Mexico that was located east of the Pecos River (Fig. 3). Not until about 1849 was its present geographic position west of the Pecos recorded. Whether the name

[8] In possession of the New York Historical Society, New York City.

Guadalupe came to be applied to the mountains by this means or by an alternative course from the Shrine of Guadalupe is not known. This shrine, located 3 miles from Mexico City, Mexico, was established shortly after the supposed appearance of the Madonna to a poor Mexican on Saturday, December 9, 1531. Salt Flat, which lies west of and at the foot of the Guadalupe Mountains, very shortly after the Spanish conquest became a source of salt for Mexico City and as the pioneer trade route to Santa Fe crossed the Rio Grande at El Paso del Norte, these mountains were virtually in sight of the travellers. Thus the hardy adventurers had two natural means of approach to the mountains: (1) a course up the Pecos Valley from the Gulf Coast, a route that later became much used in the 19th century, and (2) the inland trade route from Mexico City to the upper Rio Grande Valley. There appears, however, to be no specific record indicating from which source the Guadalupe Mountains received their name.

The Guadalupe Mountains end southward in a bold precipitous promontory 1,300 feet high, which is formed by the Capitan limestone set upon a pedestal of sandstones belonging to the Delaware Mountain formation (frontispiece). This magnificent scarp, visible for a radius of more than 100 miles, is referred to by the inhabitants of the region as Guadalupe Point, the Point of the Guadalupes, or the Point of the Mountains, the last two terms having a more inclusive interpretation covering not only the Point but also the wedge-shaped area immediately back of the Point. One mile north of the Point (8,078 feet) is the Peak (8,751 feet), the highest part of the Guadalupes, and also the highest point in Texas (Fig. 14). It was known to the Apache Indians as Smoke Mountain, for from its summit they signalled for great distances by means of smoke and flame. The name "Sentinella," which strangely appears on the excellent map of Col. Monroe of the U. S. Topographic Engineers of 1851 and is a variation of the Spanish centinela, meaning sentinel or signal, may have reference to this fact. Both the old settlers and those living within the mountains know of it as Signal Peak.

Early descriptions by Bartlett, Pope, Shumard, and Hill lack precision with reference to the Point and the Peak. Though Hill used Guadalupe Peak on his map of Texas and New Mexico (1899), his descriptions are not consistent. Tarr states "the point of the mountains is a precipice in white magnesian limestone fully two thousand feet high, which suddenly terminates the mountain" and "is just south of Guadalupe Peak, the highest point." Richardson, in his reconnaissance of the trans-Pecos, introduced in 1904 the name El

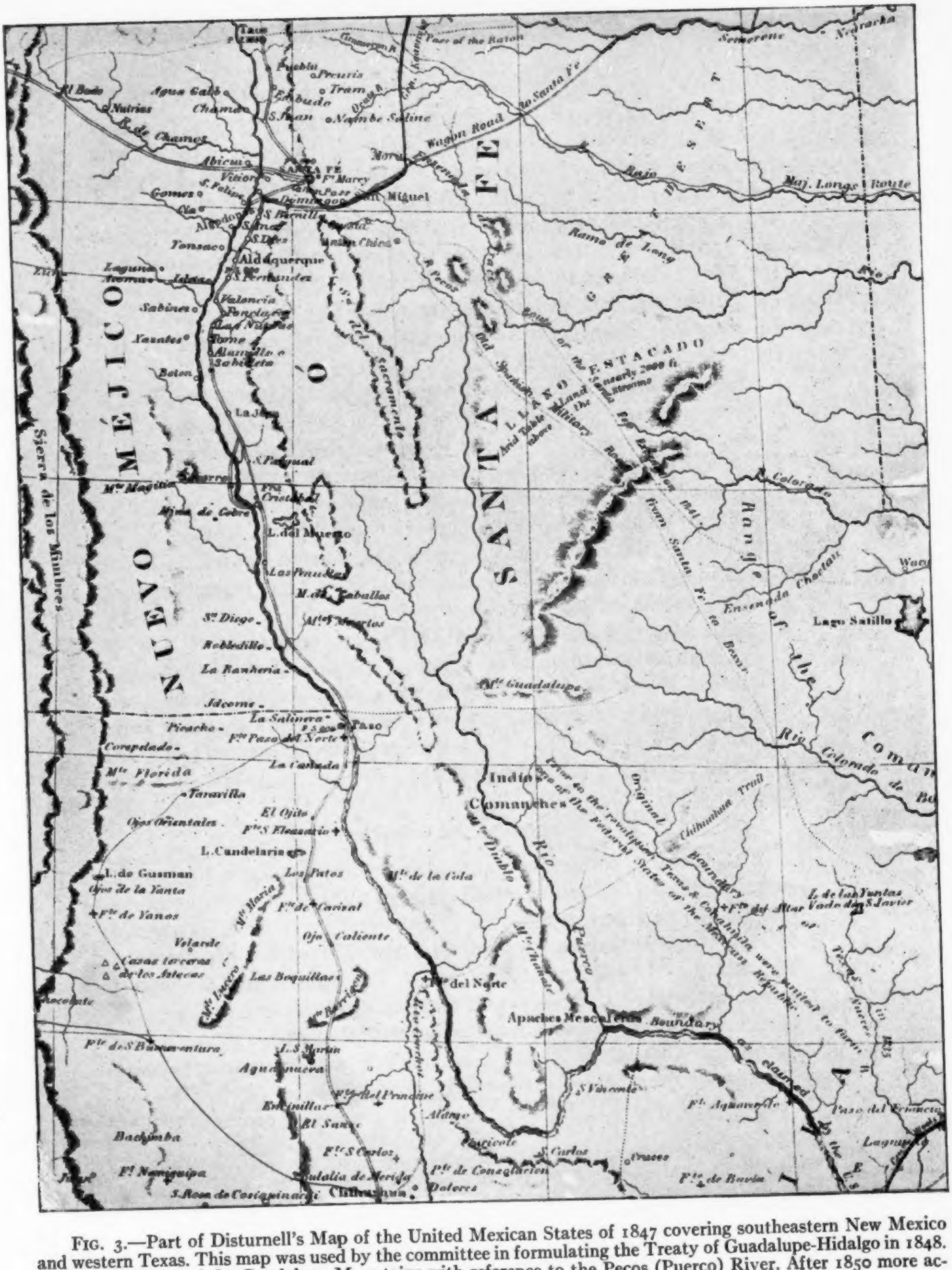


FIG. 3.—Part of Disturnell's Map of the United Mexican States of 1847 covering southeastern New Mexico and western Texas. This map was used by the committee in formulating the Treaty of Guadalupe-Hidalgo in 1848. Note the position of the Guadalupe Mountains with reference to the Pecos (Puerco) River. After 1850 more accurate maps of the area began to appear.

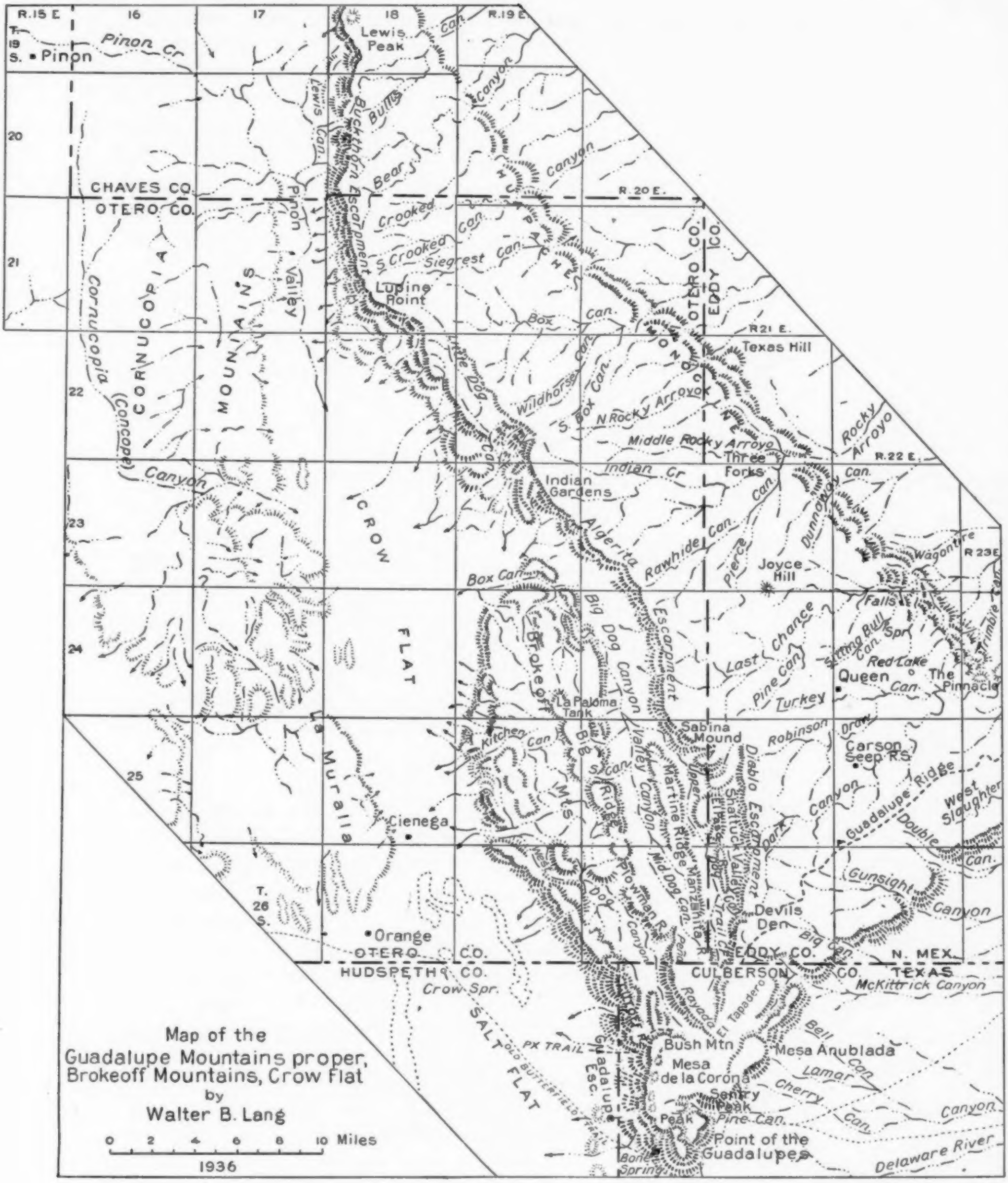
Capitan for the Peak, following information that was given him by ranchers living in the flat. This name has found general usage in geological literature. In 1909 the United States Coast and Geodetic Survey referred to this summit as Cone Peak. Unfortunately the name El Capitan is in conflict with that of a high peak (10,083 feet) of the Capitan Mountains of New Mexico, 120 miles farther north, and each is visible from the other on clear days. A recent decision of the Board of Geographic Names makes the name Guadalupe Peak official for the Peak and applies the name El Capitan to the Point. In this paper these features are hereafter referred to as the Peak and the Point.

The Guadalupe fault.—The Guadalupe fault or fault zone, as it is in some places a multiple fault, lies along the eastern side of Salt Basin, which is one of the largest internal drainage depressions in the Southwest (Fig. 26). The fault line trends north 20° W. and extends 150 miles (Fig. 1) from the Davis Mountains in Texas to the head of Lewis Canyon in New Mexico, where the Guadalupe Mountains merge with the Sacramento cuesta. It forms the western boundary of the Guadalupe, Delaware, and Apache mountains. The greatest amount of displacement, which occurs in the vicinity of Salt Flat, gradually diminishes northward to Four Mile Canyon on the north side of Lewis Peak, where there is no apparent rupture of the San Andres limestone. North of Four Mile Canyon and west of Dunken an east-dipping monoclinal fold appears to be a reversal of the fault and an extension of it. The scissors point lies in the vicinity of Four Mile and marks the intersection of the two structural systems of the region.

THE BROKEOFF MOUNTAINS

The Brokeoff Mountains[9] are, as the name implies, a broken-off segment of the Guadalupe Mountains as a result of multiple hinge faulting in the Dog Canyon area (Figs. 2 and 4). A series of parallel valleys and ridges have resulted from the differential displacement and tilting of the blocks in the back reef. The massive reef limestones were apparently more competent and the displacement of the rocks here has been concentrated more or less in a single fault plane, which forms the Guadalupe Escarpment. Much minor faulting occurs throughout the Brokeoff Mountains, though where they make connection with the Guadalupes faulting is especially prominent. The

[9] These mountains have not before been known by name. To them is here given the name Brokeoff Mountains. Some ranchers have used Brokeoff for Cutoff Ridge, the precipitous west-facing ridge which lies between the PX trail and West Dog Canyon. For this ridge the name Cutoff Ridge is retained.


Map of the
Guadalupe Mountains proper,
Brokeoff Mountains, Crow Flat
by
Walter B. Lang
0 2 4 6 8 10 Miles
1936
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R.19 E
R.20 E.
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R.22 E.
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T. 26 S.
Pinon
Pinon Cr
Lewis Peak
Lewis Can.
Buckthorn Escarpment
Bulls
Canyon
Bear
Canyon
CHAVES CO.
OTERO CO.
Crooked
S. Crooked Can.
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Lupine Point
APACHE
Box Can.
OTERO CO.
EDDY CO.
Texas Hill
Cornucopia
CORNUCOPIA
MOUNTAINS
Pinon Valley
Cornucopia (Concepel) Canyon
Wildhorse Can.
S. Box Can.
N Rocky Arroyo
Middle Rocky Arroyo
Rocky Arroyo
Three Forks
Indian Cr
Indian Gardens
Can.
Dunnaway Can.
CROW
FLAT
Algerita
Rawhide Can.
Pierce
Joyce Hill
Wagontire
Trimble Can.
Box Can.
Big Dog Canyon
Escarpment
Brokeoff
Last Chance
Falls
Sitting Bull Can. Spr.
Red Lake
Pine Can.
Queen
The Pinnacle
Turkey
Can.
La Paloma Tank
Sabina Mound
Robinson
Draw
Carson Seep R.S.
Kitchen
Can.
Big
S. Can.
Valley
Canyon
Martine Ridge
Diablo Escarpment
Mts
Ridge
Upper
Shattuck Valley
Canyon
Guadalupe Ridge
West Slaughter
Double
Can.
La Muralla
Cienega
Gunsight
Canyon
Mid Dog Can.
Manzanita R.
Devils Den
Big
Orange
OTERO CO.
EDDY CO.
N. MEX.
HUDSPETH CO.
CULBERSON CO.
TEXAS
McKittrick Canyon
Crow Spr.
El Tapadero
Bell
SALT FLAT
PX TRAIL
OLD BUTTERFIELD TRAIL
Guadalupe Esc.
Bush Mtn
Mesa Anublada
Mesa de la Corona
Lamar
Can
Sentry Peak
Cherry
Can
Canyon
Peak
Pine Can.
Point of the Guadalupes
Delaware River
Bone Spring

FIG. 4

Brokeoff Mountains are composed essentially of Dog Canyon and San Andres limestones, and interfingering sandstones are most conspicuous at the south end. The beds are slightly arched. Faults paralleling the axis of the mountains interrupt the continuity of the beds. Cross faults are also present. The dip is northwestward, very slight at the southeast, but increasing greatly in degree in the western and northern parts of the mountains. South Canyon exposes a section of Dog Canyon limestone overlying the San Andres. On the steep west face of Cutoff Ridge some of the strata lie at a steep angle on the face of the slope, and their attitude is probably a consequence of fault drag and erosional slumping.

DELAWARE MOUNTAINS

Directly[10] south of the Guadalupe Mountains are the Delaware Mountains. Together they form an integral part of the western margin of the eastward-dipping Guadalupe monocline which is faulted on its west side. The Delawares are far less imposing mountains than their northern neighbor, rising only to elevations of 5,500 feet. They are composed of sandstones laid down in the Delaware basin, which are less resistant than the limestones in the Guadalupe Mountains farther north. The western, or limestone rim of the basin has in this region been faulted off, and engulfed in the graben valley of Salt Basin. The west-facing bajada slope exposes the sandstones and limestones of the Delaware Mountain formation. The cuesta slope is gentler than the dip of the rocks and it is therefore capped by younger formations of the Permian, Triassic, Cretaceous, and Quaternary, as one progresses eastward to the Pecos Valley.

SACRAMENTO MOUNTAINS

Northward the Guadalupe monocline merges with the median portion of the eastward tilted Sacramento monocline (Fig. 1). The crest of the Sacramento Mountains occupies the western rim of this monocline and lies 80 miles west of the Pecos River. The Guadalupe monocline joins the Sacramento monocline at Lewis Canyon only 40 miles west from the Pecos River. The western slope of the Sacramento Mountains is composed of two abrupt steps and exposes rocks of pre-Cambrian to Permian age. The first step down includes the Permian rocks; the second step the Pennsylvanian to pre-Cambrian

[10] The name is derived from the Delaware Indians. They originally lived on the Atlantic coast but refusing to submit to colonial control moved westward into Ohio. With subsequent encroachment by the white settlers into the Ohio and Mississippi valleys, the remnant bands of these independent Indians moved on into Oklahoma and Texas.

rocks. In north-south section this western exposure facing the Tularosa basin appears as a broad flat anticline. On the north are the post-Cretaceous intrusions of the Sierra Blanca and Capitan Mountains, the latter having an anomalous east-west trend. The Sacramento cuesta is essentially a dip slope and the San Andres limestone caps practically all of it. In minor folds and in canyons older rocks are revealed.

THE PECOS VALLEY AND THE LLANO ESTACADO

The cuesta slopes of both the Sacramento and Guadalupe mountains are interrupted by a cover of younger formations east of the Pecos River, which rise eastward by steps to the Llano Estacado or cap rock. The Llano Estacado is a very flat plain with a slight southeastward slope. It is underlain by a variable thickness of Tertiary sands and gravels deposited upon a floor of Triassic and Cretaceous rocks. It is capped by a Quaternary (?) caliche approximately 10 feet thick, which is in turn covered in places by Recent windblown sands and silts. The deposits of the plain thin out toward the south where the Cretaceous rocks of the Edwards Plateau come to the surface. The escarpment of the Llano Estacado facing the Pecos Valley in places attains a height of 200 feet or more and exposes Tertiary and Triassic deposits along its base. In other places the scarp fades out and is almost unrecognizable as such. Between the Llano Estacado and the Pecos River are younger caliche caps and irregular accumulations of residual and windblown sands. The geographic feature known as the "Mescalero Sands" lies immediately west of Mescalero Ridge, the western escarpment of the Llano Estacado.

DESCRIPTIONS OF CROSS SECTIONS

Some rock formations of the Pecos Valley of New Mexico and Texas, although simple in structure, are of a complex sedimentary character and have for that reason proved difficult of correlation. Many of the units are chemical in origin, lenticular, and non-fossiliferous. Those that are fossiliferous in many places change facies within short distances or terminate abruptly. West of the Pecos River in the Delaware, Guadalupe, and Sacramento mountains, more fossiliferous Permian rocks crop out. East of the Pecos they dip beneath younger sediments and are known only by drill records.

The section shown in Figure 5 is a diagrammatic representation of the Permian formations of the Pecos Valley, generalized and simplified to incorporate the essential features discernible both in outcrop and in sub-surface. The section was drawn along a north-south

line parallel to the Lea-Eddy County boundary, originating at a point a few miles south of the Texas line and extending northward to the latitude of Roswell, New Mexico. Figure 6, which shows similar stratigraphic features, was drawn along an east-west line extending through the south end of section, Figure 5. In it the Upper Permian formations on the west have been removed by erosion. This leaves exposed the Capitan and Carlsbad limestones, which on the eastern side of the Delaware basin are buried beneath 3,000 feet of sediments, including the Triassic redbeds.

LATERAL AND VERTICAL ARRANGEMENT OF THE FORMATIONS

It is apparent from these sections that the formations within the Delaware basin, along its rim and beyond, are not all simple continuous units apparently flexed by structural movement, but terminate sharply, interlocking with or overlapping their contemporaneous neighbors. The lithologic change is generally abrupt and most of these transitions occur in the space between two monoclinal flexures, whose axes serve to define three sedimentary provinces. Nomenclature of the formations is grouped into three geographic zones: (1) the Delaware basin or fore-reef province, (2) the reef-zone province, and (3) the back-reef province. These provinces are continuous about the rim of the basin. By confining the names of several of the formations to their respective zones, three geographic provinces are established with a set of geologic names for each province.

The Permian may also be divided vertically into three parts—the Lower Permian, which is represented by the Bone Spring limestone and the equivalent units down to and including the Abo sandstone (=Wolfcamp); the middle or Delaware Mountain time unit, which includes the period of greatest reef development; and the upper or sequence of chemical precipitates. These separations are shown on Figure 5 by heavy lines and represent periods of marked depositional change and structural movement in the Permian of this area. The marine facies of the Permian is best represented in the Delaware basin and attained its maximum in Bone Spring (=in part Chupadera) time. The Delaware Mountain formation interfingers in the reef zone into formations that change abruptly into different lithologic units constituting a series of reef growths. The Lamar limestone member is correlated with the top of the Carlsbad limestone (Fig. 21). The back-reef zone was the realm of chemical precipitation during the various stages of reef building. None of the major formations escaped the inclusion of sediments of chemical origin. The precipitation of chemical sediments reached a maximum in Salado time and

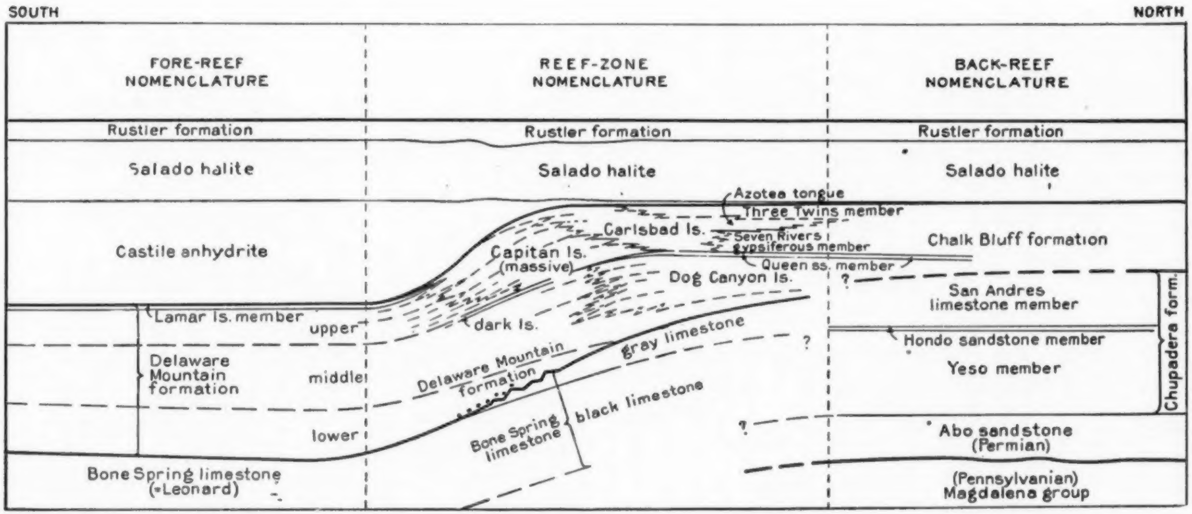

FIG. 5.—Idealized north-south diagrammatic section across the Permian reef zone from points N to S. Nomenclature of the formations is grouped into three zones: the Delaware basin province or fore-reef zone, the reef-zone province, and the back-reef province.

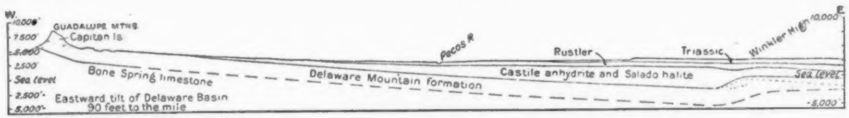

FIG. 6.—A west-east cross section south of the Texas-New Mexico boundary across the northern portion of the Delaware basin.

spread with greater continuity and uniformity over this area than did any other Permian formation of this type.

FORMATIONS OF THE BACK REEF

ABO SANDSTONE

The Abo sandstone is the basal formation of the Permian in southeastern New Mexico. It was named by Willis T. Lee[11] in 1909 from Abo Canyon at the southern end of the Manzano Mountains. It is also exposed on the western or bajada slope of the Sacramento Mountains, where, dipping slightly eastward in conformity with the overlying formations of the cuesta, it descends beneath the Pecos Valley to be encountered only by wells drilled to great depth. The Abo is 700 feet thick in the Sandia Mountains, in north-central New Mexico, 650 feet at Abo Canyon, 700 feet at the north end, and 400 feet at the south end of the Sacramento Mountains, where it continues to thin and to change in character south of the Texas line to a black marine limestone with clastics. The Abo is considered the northern representative of the Wolfcamp formation of the Glass Mountains. In central New Mexico the Abo shows many of the features of a terrestrial deposit. Here well preserved plant fossils are to be found and marine life is absent except in the two thin limestone members at the base, where marine forms are associated with fine shale and conglomerate. Ripple marks and strand-line markings are in the red shaly sandstones, as are also well developed hopper-shaped pseudomorphs of halite crystals. Reptile bones are reported from Rio Arriba County, New Mexico. Arkose, though present farther south, becomes a prominent constituent of the Abo in northeastern New Mexico, where the Amarillo-Wichita granitic highs and the ancestral Rocky Mountains contributed an abundant supply of arkosic material. The dominant color of the Abo is a strong brownish red. This is of great assistance in subsurface determinations, where it lies between the gray Magdalena (Pennsylvanian) below and the grayish Yeso (Permian) above and is recognizable without difficulty. Some of the shaly sandstone members show a purplish hue, a distinguishing characteristic. The Abo with the Yeso and San Andres compose Lee's Manzano group. The angular unconformity between the Magdalena and the Abo, quite evident in some areas, is apparently not everywhere found.

[11] Willis T. Lee and George H. Girty, "The Manzano Group," *U. S. Geol. Survey Bull. 389* (1909), p. 12.

CHUPADERA FORMATION

In 1922 Darton[12] introduced the term Chupadera to embrace the Yeso and San Andres where it was difficult to recognize these units as separate entities in surface mapping. Areas still remain in which insufficient work has been done to establish a separation, especially where lithologic changes make the two less distinctive, and it is now considered desirable to retain the term for a formation and include under it, as members, the Yeso, Hondo, and San Andres. Later, as knowledge of the distribution of these rocks increases, especially with the support of additional drill records, there will be less need for this blanket term. The name was taken from Chupadera Mesa in central New Mexico (Fig. 1).

In 1933 Nye[13] applied the names "Picacho limestone" and "Nogal formation" to lithologic units in the Roswell artesian basin. His type sections were taken in Hondo Valley and Tularosa Canyon, respectively, and are essentially the equivalent of San Andres, Hondo, and Yeso, as here defined. He extended his Picacho limestone approximately 50 feet below the Hondo sandstone. As there is no need for a duplication of terms, Nye's names have here been discontinued in favor of the original names of Lee. A comparison of the formations of the Manzano group of Lee with the present classification in the Pecos Valley is given in the following table.

	San Andres Mountains	*Pecos Valley of Southeastern New Mexico*	
Manzano group of Lee (1909)	San Andres limestone	San Andres limestone member	Chupadera formation
		Hondo sandstone member	
	Yeso formation	Yeso member	
	Abo sandstone	Abo sandstone	

Yeso member.—The Yeso was named by Lee[14] in 1909 from Mesa del Yeso, 12 miles northeast of Socorro, New Mexico (Fig. 1). The Yeso, like many of the Permian units, is so variable in composition that no simple description will hold true for all localities, for it varies from place to place by lateral gradation. It is essentially grayish with some red coloration and has a chalky appearance on outcrop due to the presence of numerous thick beds of anhydrite which weather to gypsum. The intercalated black limestones are commonly

[12] N. H. Darton, "Geologic Structure of Parts of New Mexico," *U. S. Geol. Survey Bull. 726*, Pt. II, p. 181.

[13] S. S. Nye, "Geology and Ground-Water Resources of Roswell Artesian Basin," *U. S. Geol. Survey Water-Supply Paper 639* (1933), pp. 55 and 70.

[14] Willis T. Lee and George H. Girty, *op. cit.*, p. 12.

concealed by this cover of gypseous material (Fig. 7). The Yeso is composed of sandstone, soft, medium to fine-grained, and grayish, yellowish to pinkish in color, massive anhydrite beds, earthy gray to dense black limestones and dolomitic limestones, and soft red shales. It ranges from 600 to 2,000 feet in thickness. It is distinguishable from the overlying San Andres by the predominance of sandstone and anhydrite, whereas the San Andres is essentially a limestone with included sandstone, anhydrite, and red shale beds. The black limestones are fossiliferous and carry a *Bellerophon* and *Euomphalus* fauna. In the rocks that are not exposed, beneath the cuesta of the Sacramento Mountains, lenses of clear rock salt are included with the anhydrite. The thickness of the Yeso in well records is commonly 1,000–1,500 feet. It appears at the surface on the western flank of the Sacramento Mountains and is well exposed in Tularosa Canyon.

The erosion of Tularosa and adjacent canyons and the transportation of the dissolved sulphates to the west side of Tularosa basin are processes that undoubtedly have been important contributors to the ultimate formation of the geographic feature known as the "White Sands." Similar gypsum sands occur in Salt Flat west of the Guadalupe Mountains. Both the Yeso and San Andres are cut by numerous small igneous dikes and sills which are apophyses from the main intrusion that constitutes the Sierra Blanca, Capitan, and associated igneous masses. Many of these sills are to be seen in the Rio Bonito and Ruidosa valleys.

Hondo sandstone member.—A sandstone bed that crops out near the bottom of the valley of the Hondo and its tributaries has proved of great value in subsurface correlation in southeastern New Mexico. It may be observed in well sections north of the Delaware basin in this southeastern area, and serves to separate the Yeso from the San Andres. It has been commonly referred to in the field as "Glorieta sandstone," although it has never been definitely shown that this particular sandstone is wholly or in part the sandstone of Glorieta Mesa, in northern New Mexico. The name Hondo sandstone is therefore here given to this unit. This sandstone, variably streaked yellowish to brownish red, is composed of coarse white quartz grains and is cemented by iron and lime. In places, cross bedding is apparent and iron concretions and nodules are abundant in the upper part of the sandstone. It is commonly about 50 feet thick. This sandstone crops out in places along the base of Algerita Escarpment facing Dog Canyon.

San Andres limestone member.—The San Andres limestone was

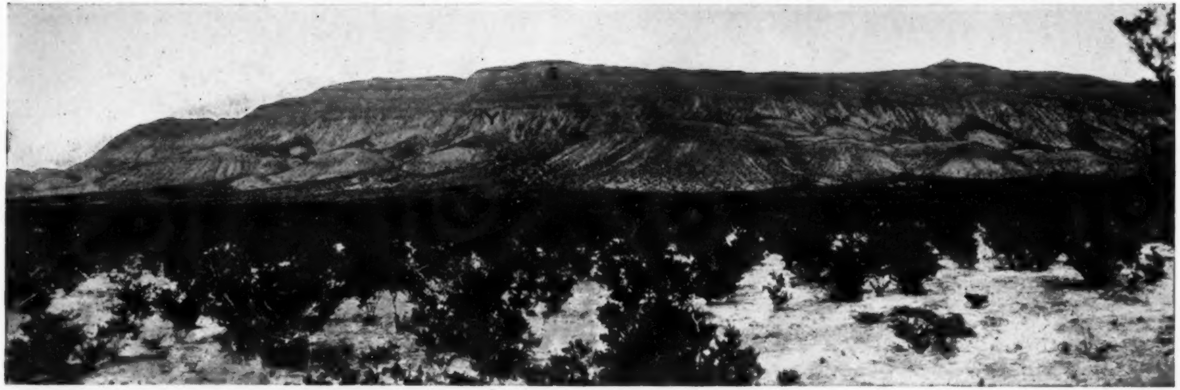

FIG. 7.—A view of the north wall of Tularosa Canyon near Tularosa, New Mexico. Shows the San Andres limestone (s) overlying the Yeso formation (y). The Abo is covered by wash in the foreground.

FIG. 8.—Looking west from the Yeso Hills across Black River Valley to the Barrera. Twenty-five miles of the southwest part of the reef front are shown, from Slaughter Canyon to the Point of the Guadalupes. The Point is one of the most conspicuous landmarks in the Southwest and visible for a distance of more than 100 miles.

named by Lee[15] in 1909 from a prominent exposure on the western dip slope of the San Andres[16] Mountains. In the Pecos Valley the San Andres limestone serves as the cover rock of the Sacramento cuesta from Cloudcroft to the Pecos River, where it dips beneath younger rocks on the east side of the valley. The San Andres limestone is about 1,200 feet thick and is composed of massive black limestones, grayish hackly and yellowish earthy limestones, and dolomitic limestones with included sandstones, anhydrite, and redbeds. Some of the upper beds are thin and platy. The anhydrite and redbeds gradually replace the upper limestones farther northeast.

On Figure 1 a dashed line has been drawn indicating the highway west from Roswell up the Hondo and Ruidosa valleys across the Sacramento Mountains, descending Tularosa Canyon and across Tularosa basin to the San Andres Mountains. The San Andres limestone comes to the surface from beneath valley fill just west of Roswell (3,600 feet elevation). The eastward inclination of the limestone beds is slightly greater than the average surface gradient and hence as the road goes westward it gradually traverses deeper beds of the San Andres. On descending Picacho Hill, it crosses both the base of the San Andres limestone and the Hondo sandstone. From here the highway follows the Hondo sandstone part way up the Hondo Valley and then descends into the Yeso section. In the Ruidosa Valley west of Eagle Creek, it again rises into the San Andres section. After crossing the divide at the altitude of 7,600 feet in the Mescalero Indian Reservation, the road descends in altitude and again in section, passing quickly out of the San Andres into the Yeso, on which it continues to the vicinity of Bent, completing the remaining distance to Tularosa (4,700 feet elevation) on the Abo and Magdalena. Beyond the Tularosa basin the section is again duplicated after an ascent of older rocks in Rhodes Canyon in the San Andres Mountains where the Abo, Yeso, and San Andres may be readily recognized. Here the beds dip toward the west and were at one time continuous eastward as an arched fold, connecting with the eastward-dipping beds of the Sacramento Mountains. Faulting and the collapse of the arch developed the broad Tularosa basin. The Yeso may be carried from here northward to Mesa del Yeso.

A section on the northern escarpment of Tularosa Canyon northwest of Bent shows the following thicknesses.

San Andres limestone	621 feet	Upper part eroded
Hondo sandstone	12 feet	
Yeso	1,050 feet	Base concealed

[15] Willis T. Lee and George H. Girty, *op. cit.*, p. 12.

[16] Originally spelled San Andreas (Italian) and changed by the Geographic Board to the Spanish form of spelling, San Andres.

FIG. 9.—View of the back reef deposits, looking southeast from Cutoff Ridge (elevation, 6,900 feet) toward Blue Ridge. Carlsbad limestone (Ca), Capitan limestone (C), Dog Canyon limestone (DC), middle Delaware Mountain (mD), gray limestones (gl).

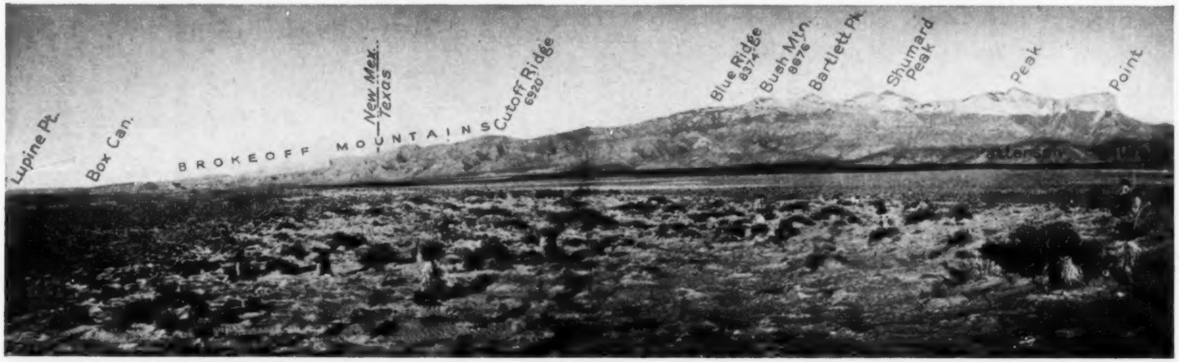

FIG. 10.—A panorama from Lupine Point to the Patterson Hills viewed from the north end of Salt Flat and showing the reef limestones exposed on the Guadalupe Escarpment and the Brokeoff Mountains. Some of the sand in the foreground is composed of gypsum. Elevation of foreground, 3,650 feet.

The base of the San Andres limestone lies just below the crest of the divide between the Sacramento River and Grapevine Canyon at the south end of the Sacramento Mountains. On the southern rim of the Sacramento cuesta, the San Andres dips southward and good fossiliferous exposures are to be seen in Chatfield and Surveyor canyons. This southward dip continues in the Cornucopia Mountains, which are composed of San Andres limestone. However, in Buckthorn escarpment (Fig. 4) on the east side of Pinon Valley, these same San Andres limestone beds continue horizontally southward in the Guadalupe Mountains and in the Dog Canyon area become covered by an increasing thickness of younger rocks. Southward from the mouth of Cornucopia Canyon on the west side of Crow Flat the dark fossiliferous limestone changes facies and becomes more non-organic in appearance and the limestone exposed in La Muralla, possesses a Dog Canyon aspect. Farther westward the basal part of the San Andres limestone occurs in the Cornudas Mountains in contact with the laccolithic body of igneous rocks in these mountains. Immediately south of the Cornudas a thick section of Yeso sediments is exposed.

In Grapevine Canyon (Fig. 1) the Magdalena, Abo, Yeso, and San Andres are exposed. The San Andres may be traced eastward to Pinon and down Pinon Creek to the north end of the Guadalupe Mountains. The floor of this canyon lies within the mid-section of the San Andres. Where Pinon Valley opens into Crow Flat, both escarpments, Buckthorn on the east and the Cornucopia Mountains on the west, are composed of San Andres limestone, fossiliferous and dark gray. It continues southward to the re-entrant of Big Dog Canyon, where a great mass of the San Andres limestone is found slumped upon the canyon floor. Just within Big Dog Canyon the Yeso formation comes to the surface at the base of Algerita Escarpment. The Yeso formation disappears below the surface before reaching Sabina Mound (Fig. 4). In Big Dog Canyon along Algerita Escarpment and southward in Upper Dog Canyon the limestone of the top part of the escarpment becomes more whitish and non-organic in appearance. Here in Upper Dog Canyon near Manzanita Tank sandstones interfinger with the limestone beds and they increase in thickness and number toward the reef zone. This section also increases in total thickness and finally merges with the Dog Canyon reef head.

The San Andres limestone, which lies below the Dog Canyon limestone, makes up most of Algerita Escarpment of Big Dog Canyon and can be traced into Upper Dog Canyon, but for various reasons it can not be carried into precise relationship with the section below

Bush Mountain on the Guadalupe scarp without assumption or detailed field correlation. The intervening area is most complex; lithologic changes take place within short distances; the limestones become similar in character and are intercalated by numerous sandstones which are also repetitional in kind and color. This situation is further complicated by considerable faulting.

Sufficient data for precise correlation of the San Andres limestone of the Sacramento cuesta with the reef formations is therefore not yet available. On paleontologic grounds (*Productus ivesi*, etc.) the San Andres is correlated with the Bone Spring and Leonard through the gray limestone. It is also a correlative of the Kaibab limestone of Arizona and Utah and the Blaine of Texas and Oklahoma, which provides a broad general datum plane. This, however, does not imply an exact equivalence with them all. On the basis of stratigraphic correlation in the back-reef area of the Guadalupe Mountains, it appears that the San Andres is higher in the section and must in part be equivalent to some portion of the middle Delaware Mountain. If such is the case, it places the very obvious sedimentary break between the Delaware Mountain and the Bone Spring within the San Andres or at its base and makes the Dog Canyon limestone in part equivalent to the San Andres. Recognition of the Hondo equivalent in the reef and fore-reef areas is needed in order to correlate the base of the San Andres. In West Dog Canyon the exposed sections may not go deep enough, but in the vicinity of the PX trail the Hondo or its equivalent should be found.

Despite the hazards involving correlation by stratigraphic means in this complex area, this method is more likely to prove satisfactory than paleontologic evidence. Paleontology has yet to provide key fossils of sufficiently limited vertical range and of such lateral persistance throughout the variant environments so common in the Permian reef areas as to serve the present need for finer subdivisions. In this respect the fusulinids are a possible hope, more especially in subsurface correlation. To date, their value seems to be limited to gross, long-range comparisons, involving sections many hundreds of feet thick.

CHALK BLUFF FORMATION

Above the San Andres limestone in wells east of the Pecos River, in the latitude of Artesia and Roswell, is found a sequence of beds that consist of anhydrite, dolomitic anhydrite, sandstone, redbeds, and dolomitic limestone. This sequence makes up a formation about 1,000 feet thick, and through interfingering on the south with dif-

ferent units, the Queen sandstone, Seven Rivers, and Three Twins members, and the Dog Canyon and Carlsbad limestones, changes into the Delaware Mountain formation. It is believed to be the approximate equivalent of the Whitehorse sandstone of Oklahoma. The Chalk Bluff formation derives its name from Chalk Bluff (Fig. 2), the east bank of the Pecos River southeast of Artesia, and consists of all sediments lying between the San Andres limestone and the Salado halite. A thin tongue of Castile anhydrite may extend northward from the Delaware basin and intervene between the Salado and the Chalk Bluff. One of the interesting features of the Chalk Bluff formation is the inclusion of numerous beds of greenish bentonite, some of which attain a thickness of 5 feet or more. Both the thickness and the color of these bentonite beds vary. The thicker beds appear to have accumulated in shallow pockets along the bottoms and in such localities they are invariably clear sea-green, coppery green, or gray-green. Thinner seams are more likely to be gray, brown, or red. The bentonite beds serve as excellent stratigraphic markers.

Richardson, in 1903,[17] recognized the presence of redbeds above the Rustler. Since then, these redbeds, along with others occurring east of the Pecos, have received little study, and have been variously classified to suit the particular occasion. They were generally referred to as the "Redbeds of the Pecos Valley." Darton[18] grouped them with the Chupadera or the Rustler on the geological map of New Mexico. Nye[19] included all the Permian above his Picacho (=San Andres) in his Pecos formation. Most of the sediments to which he refers as the "Pecos formation" are the Chalk Bluff, the Salado having been truncated and the Rustler overlapped on the west of the basin by the Triassic and surficial deposits. These formations—the Chalk Bluff, possible remnants of the Castile, Salado, Rustler, and the Triassic—supplant the Pecos formation. Surface exposures are either poor or absent altogether, excepting the Chalk Bluff, which has been cut by the Pecos River, forming in places low bluffs on the east side of the river. These formations, however, are easily recognized in well records from the Maljamar or south Lea County areas (Fig. 1). The Rustler is here essentially an anhydrite with redbeds; the dolomitic members are generally absent or poorly represented. Beneath the Rustler is a thick section of more than 1,000 feet of the Salado halite,

[17] G. B. Richardson, "Reconnaissance in Trans-Pecos Texas, North of Texas and Pacific Railway," *Univ. Texas Mineral Survey Bull. 9* (1904), p. 45.

[18] Geologic map of New Mexico, U. S. Geol. Survey, 1927.

[19] *Op. cit.*, p. 44.

which contains beds of anhydrite and polyhalite. The Salado[20] is underlain by the Chalk Bluff dolomitic anhydrites, sandstones, and redbeds. The Chalk Bluff is a back-reef formation (Fig. 5), but is represented in part of the reef province by the lithologic units that have been named the Twin Hills, Seven Rivers, and Queen sandstone members of the Chalk Bluff, and by the Dog Canyon limestone.

The Chalk Bluff formation is equivalent to the unit farther east that has been called by the subsurface geologists the Whitehorse or Whitehorse-Cloud Chief.[21] Near the top of the so-called Whitehorse-Cloud Chief, a widespread layer of sandstone has been recognized by them which is known as the Yates sand.[22]

SUBDIVISIONS IN THE REEF ZONE

THE LOWER BEDS

The lowest beds exposed in the reef area are limestones considered by the writer to be transitional from a part of the Chupadera into the Bone Spring. The correlation of the San Andres with the beds on the south has been much disputed. By some the San Andres has been thought to be equivalent to the Capitan limestone, but the Capitan does not hold its character as a solid limestone very far northward from its type locality. Field work by other geologists has suggested a tracing of the San Andres into beds here designated as the Dog Canyon limestone and it is not unlikely that they are in part related even though the Dog Canyon in the reef zone does not resemble the San Andres either lithologically or faunally. However, a more complete paleontologic study may find this apparent faunal difference less real.

The beds which most resemble the San Andres in the reef zone are the gray limestones in the upper part of the Bone Spring formation. According to observations of P. B. King,[23] these gray limestones near the New Mexico-Texas line comprise a group of thick-bedded, sparingly cherty, gray limestones, about 300 feet thick, which contain

[20] W. B. Lang, "Upper Permian Formations of Delaware Basin of Texas and New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19 (1935), pp. 262–70.

[21] L. D. Cartwright, Jr., "Trans-Pecos Section of Permian Basin, West Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14 (1930), pp. 972–73.
H. P. Bybee, E. F. Boehms, C. P. Butcher, H. A. Hemphill, and G. E. Green, "Detailed Cross Section from Yates Area, Pecos County, Texas, into Southeastern New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15 (1931), p. 1091.
J. E. Adams, "Upper Permian Stratigraphy of West Texas Permian Basin," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19 (1935), pp. 1013–16.

[22] G. C. Gester and H. J. Hawley, "Yates Field, Pecos County, Texas," *Structure of Typical American Oil Fields*, Vol. 2 (1929), p. 488.

[23] Personal communication.

Productus ivesi and many other brachiopods identical with those of the San Andres fauna as developed in New Mexico. Black limestones underlie the gray member of the Bone Spring south of the New Mexico-Texas line, and it is possible that the lower part of the formation is equivalent to the Yeso, which, as noted, also contains many thick black limestone beds. The Hondo sandstone member in subsurface thins out southward but undoubtedly is represented by some lithologic break in the reef zone. If it is possible in the exposures of the Guadalupe Mountains to trace this member from the back-reef through to the fore-reef deposits of the Delaware basin it would serve to establish a plane of correlation in the subsurface.

Overlying the gray member of the Bone Spring south of the New Mexico-Texas line are several hundred feet of sandstones, which are a portion of the Delaware Mountain formation, much better developed farther south. Beds of the Delaware Mountain older than these sandstones have passed out northward by overlap on the Bone Spring limestone and beds younger have intergraded northward into the Dog Canyon and Capitan limestones. These sandstone beds thin out north of the New Mexico-Texas line, a fact early recognized in subsurface farther northeast.

DOG CANYON LIMESTONE

The name Dog Canyon limestone is here given to an assemblage of rocks which lie beneath the Queen sandstone and above the San Andres limestone. On the western flank of the Guadalupe Mountains is exposed a section of bedded limestones more than 1,000 feet thick. These limestones grade along their base into the thinning sandstone of the Delaware Mountain formation and merge farther south with middle Delaware Mountain sandstones and possibly with a part of the lower portion of the Capitan limestone. Toward the north it gradually thins out above or in part merges with the San Andres limestone. The Dog Canyon limestone is overlain by the Queen sandstone member of the Chalk Bluff formation, which forms the capping of the tableland (Queen Mesa) of this part of the Guadalupe Mountains. The westward continuation of the Dog Canyon and the Queen sandstone is interrupted by faulting, but on the east the Dog Canyon limestone is again exposed on the Huapache monoclinal fold from the vicinity of Last Chance Canyon south to the Pinnacle (Fig. 4). The Huapache monocline trends N. 45° W. and is the eastern boundary of the Guadalupe Mountains proper. Last Chance Canyon and its tributaries have cut into the monocline exposing sections of the Dog Canyon beds. The limestones are buff to gray, dolomitic and

locally very sandy, the change to a sandy phase taking place irregularly and often in very short distances. This sandy phase and the abundance of large fusulinids are very suggestive of the middle Delaware Mountain exposures south of the Point. Chert is developed very prominently in some places and cross bedding is a common phenomenon. In Last Chance Canyon and Sitting Bull Cañyon, a tributary, vertical jointing of the bedded limestones is a prominent feature. In the Seven Rivers embayment limestones appear to change to gypsiferous beds and to dense inorganic limestone tongues, whereas southward the characteristically bedded limestones become more massive, and include numerous sandstones.

Crandall[24] recognized the fact that the Dog Canyon limestone is distinctly older than the Capitan, and used for it the term Chupadera, thus inferring a time connection with the San Andres which it may have in part. The Dog Canyon limestones overlie the lower sandstones of the middle Delaware Mountain. They hold the same relation to the middle Delaware Mountain section as does the Capitan to the upper part, in that they are both limestone reef phases of the sandstones of the Delaware basin.

CHALK BLUFF FORMATION

Queen sandstone member.—The Queen sandstone, a member of the Chalk Bluff formation, is best exposed on Queen Mesa (Fig. 2) in upper Dark Canyon and along the north slope of the Hess Hills in the Guadalupe Mountains. It varies in thickness from 60 to 100 feet and is a white, buff to pinkish colored fine-grained sandstone. The amount of cementation is variable, but usually increases toward the reef. In places the sandstone is extremely pulverulent and friable, the grain size being that of a silt. Thin beds of inorganic limestones are included with the sandstone member. On Queen Mesa weathered blocks of the sandstone are dull dark brown to red, giving the impression that it is a deeply colored sandstone. This is a weathering effect due to the alteration and accumulation of hydrous iron at the surface. When broken open the weathered fragments are white or variably stained yellowish. Other sand members in the back-reef area exhibit a similar habit. This sandstone member is a key horizon for separating the Carlsbad limestone and Seven Rivers gypsum above from the Dog Canyon limestone below. The sandstone is believed to pinch out at or near the base of the Capitan limestone, and above the reef head of Dog Canyon limestone. This horizon

[24] K. H. Crandall, "Permian Stratigraphy of Parts of Southeastern New Mexico and Adjacent Parts of Western Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), p. 993.

undoubtedly corresponds with the sandstone that forms the upper part of the middle division of the Delaware Mountain formation on the south side of the reef.

Seven Rivers gypsiferous member.—The Seven Rivers gypsum, so named by Meinzer, Renick, and Bryan[25] in 1926, is in part the upper member of the Chalk Bluff formation. It is best exposed along the western escarpments of the Hess Hills, Azotea Mesa, and the Seven Rivers Hills. In the re-entrant opening of Rocky Arroyo, a series of sandstones, anhydritic[26] sandstones, and redbeds, with intercalated anhydrite and thin dolomitic limestones from an inch to a few feet in thickness lies above the Queen sandstone and is capped by a thin tongue[27] of Carlsbad limestone approximately 50 feet thick. As one descends Rocky Arroyo the Carlsbad limestone gradually and then abruptly thickens, displacing the Seven Rivers (Fig. 11). This change from one lithologic facies to another occurs within a distance of less than a mile and is a classic example of the sudden lithologic transitions that occur in many places in Permian basin sediments. A conglomerate-breccia zone that is variable in thickness occurs near the top of the Seven Rivers and is continuous into the Carlsbad. The buff limestone beds of the Carlsbad change abruptly into thin fingers of dense, dark, non-fossiliferous dolomitic limestone. These limestone fingers are interbedded with sandstones, sandy redbeds, and anhydrites and, by reason of their association and composition, are believed to be the product of chemical precipitation. These non-fossiliferous dolomitic beds are predominantly cellular and in this respect resemble certain beds in the Rustler. Many of these thin, brittle beds, where enclosed between soft or soluble sediments, are found to be shattered on the outcrop. The lower portion of the Carlsbad and the Seven Rivers are contemporaneous deposits, but of different lithologic facies which grade from one to the other.

Three Twins member.—North from Little McKittrick to Spencer Draw the top of the Carlsbad limestone may be seen to grade into sandstones that in turn are in part displaced by anhydritic sands, sandy redbeds, anhydrites, fine greenish sandstones, thin greenish-gray sandy shales and dolomitic limestones. To this sequence of beds is here given the name Three Twins member of the Chalk Bluff formation from Three Twins Hills where in Spencer Draw a partial

[25] O. E. Meinzer, B. C. Renick, and Kirk Bryan, "Geology of No. 3 Reservoir Site of the Carlsbad Irrigation Project with Reference to Water Tightness," *U. S. Geol. Survey Water-Supply Paper 580* (1926), p. 13.

[26] Anhydrite beds where exposed at the surface in the Southwest are invariably found altered to gypsum.

[27] Further reference to this tongue is made under the Carlsbad limestone.

FIG. 11.—Seven Rivers Hills. View looking northeast across Rocky Arroyo. The Azotea tongue of the Carlsbad limestone, shown by dark shading, caps the hills and grades laterally into the Seven Rivers gypsiferous member of the Chalk Bluff formation.

FIG. 12.—A view northeastward from near the Pinnacle along the Huapache monoclinal fold showing exposures of Dog Canyon limestone in Trimble Canyon. This monocline rises more than 1,000 feet above Sotol Basin.

FIG. 13.—An exposure of the Seven Rivers gypsiferous member of the Chalk Bluff formation in McMillan escarpment. The beds are composed chiefly of sandstone with intercalated thin dolomitic layers and gypsum.

section is exposed (Fig. 2). This member represents the top part of the formation. It is underlain by the Azotea tongue of the Carlsbad limestone, or, where this is absent, by the Seven Rivers member. These two members, the Three Twins and Seven Rivers, which are similar lithologically, represent the greater part of the Chalk Bluff formation and are the equivalent of the Carlsbad and Capitan limestones of the reef zone.

The Three Twins and Seven Rivers members, being largely composed of weakly cemented sandstones and anhydrites, are readily eroded. Thus their rapid erosion has developed the Seven Rivers embayment and Sotol Basin and has left standing in relief the more resistant contemporaneous and older limestones of the Guadalupe Mountains proper and the Barrera (Fig. 2). West of the Pecos River very little of these members remains. Only the marginal portion of the Seven Rivers member, which lies protected beneath the tongue of Carlsbad limestone, is preserved. A remnant of the overlying Three Twins member is left exposed in Spencer Draw. East of the river they plunge underground.

CAPITAN LIMESTONE

The Capitan limestone marks the culmination of reef development in the Permian basin. It was named in 1904 by Richardson[28] from the high peak (8,751 feet) to which he had applied the name El Capitan. In the Guadalupe Mountains this formation attains a thickness of 1,600 feet. It is exposed in a belt 5 miles or less wide which lies in the shape of a horseshoe, concave toward the south, and makes the massive limestone rim of the Delaware basin (Fig. 22). This massive limestone forms the bold precipitous promontory at the Point (frontispiece) where the southeast-facing escarpment carved from the reef limestones meets the west-facing escarpment along the Guadalupe fault. It is made up of massive buff to gray dolomitic limestone.[29] The grayish limestone is dense and possesses a granular, gritty appearance on the surface. Weathered surfaces of the Capitan limestone are exceedingly rough and rasp-like. This characteristic is well shown in the Patterson Hills. Secondary calcite is common. Numerous vugs and cavities, many calcite-lined, occur throughout

[28] G. B. Richardson, "Report of a Reconnaissance in Trans-Pecos North of the Texas and Pacific Railway," *Univ. of Texas Mineral Survey Bull. 9* (1904), p. 41.

[29] The Permian reef limestones (the Capitan, Carlsbad, Dog Canyon, etc.) are invariably dolomitic and their magnesium content in many places approaches that of a true dolomite. With the exception of some beds of the Capitan, the reef and back-reef limestones contain 30–40 per cent of magnesium carbonate, and vary from pale gray to buff. The black limestones (of the Bone Spring, Yeso, etc.) are more likely to be true limestones in that they contain only a few per cent or less of magnesium carbonate.

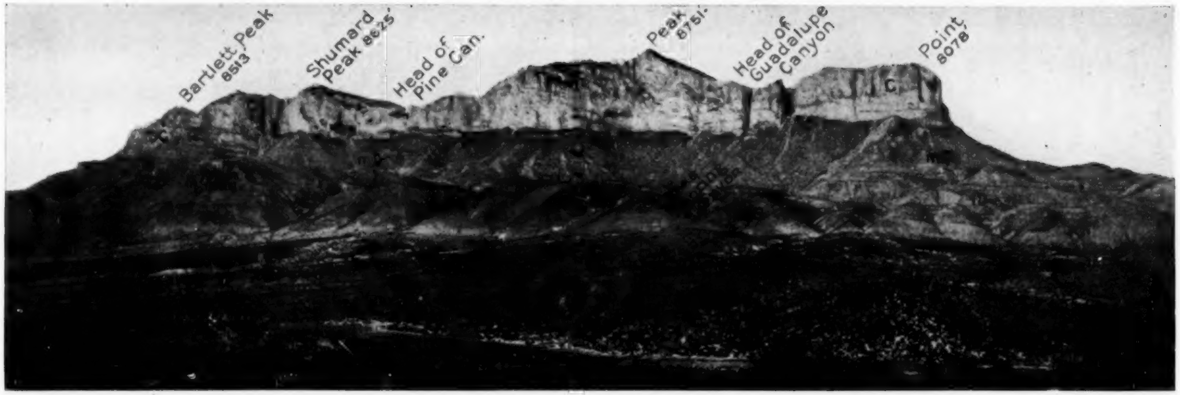

FIG. 14.—The Guadalupe Escarpment. A view looking northeast from the northern end of the Patterson Hills and 2½ miles distant from the scarp. The top of the Peak is composed of Carlsbad limestone (Ca) 100 or more feet thick and containing an abundance of fusulinids. The massive white rock is the Capitan limestone (C). At the northern end of the escarpment beneath the Capitan may be seen the whitish, more bedded Dog Canyon limestones (DC) grading into the middle Delaware Mountain (mD). The gray limestones (gl) underlie the Dog Canyon and the tongue of the middle Delaware Mountain. The lower Delaware Mountain sands (lD) pass out by overlap against the Bone Spring (BS) black limestones (dark rounded hills at the base of the escarpment).

FIG. 15.—A view of the southeastern side of the Point of the Guadalupes, showing the Point, Guadalupe Canyon, the Peak, and Pine Canyon. The Peak is capped with Carlsbad limestone (Ca). The Capitan limestone (C) may be seen intergrading with the upper Delaware Mountain sandstones (D). The basal part of the escarpment consists of the middle Delaware Mountain.

the mass. In some places cavities of large dimension are found in drilling through this limestone. Where circulating underground water has had access to this limestone, enormous caverns have developed, more especially along the reef front. The now famous Carlsbad cavern was formed in the Capitan limestone, with the exception of the upper part which is in the Carlsbad. On preliminary examination one is impressed by the massiveness of the Capitan limestone, but closer inspection reveals the presence of definite bedding planes. On the western scarp, as pointed out by Crandall,[30] curved, southward-dipping bedding planes on a magnificent scale are clearly discernible in the great exposure of limestone beneath the Peak. The frontal portion of the Capitan limestone interfingers with beds of the Delaware Mountain. This interfingering is especially well shown in Gunsight, Big, and McKittrick canyons. At those places where the sandstone beds pinch out, bedding planes that dip steeply are traceable high into the limestone. The basal portion of the Capitan is more horizontally bedded and there is some interfingering of these horizontal beds with the underlying sandstone of the Delaware Mountain formation.

The great cliff of Capitan limestone forming Guadalupe Escarpment does not trend at a right angle to the reef front (Fig. 16). Consequently, the reef dips exposed in the cliff are flatter than the true dip and changes in the thickness and attitude of the bedding are spread out over a longer distance than they would be on a line at right angles to the facies boundaries. When comparing sections through the reef and back-reef zones, it is essential to know both the distance and the direction of any point in the section from the reef front.

A test well of stratigraphic interest was drilled in the reef zone in Dark Canyon near its junction with Juniper Canyon. Dark Canyon is cut in Carlsbad limestone and some of the top beds of the Carlsbad have here been eroded off. This well, the McIntyre No. 1 of the Pecos Valley Drilling Company, was located in Sec. 35 of T. 23 S., R. 25 E., Eddy County, New Mexico (elevation, 3,583 feet). The samples show that at least 200 feet of Carlsbad was penetrated and from there to 1,930 feet or for 1,730 feet a section of Capitan was found. This is comparable to the 1,600 feet of Capitan exposed on the Guadalupe scarp. Beneath the Capitan were drilled at least 1,000 feet of Delaware Mountain sands with interbedded limestones and thin beds of

[30] K. H. Crandall, "Permian Stratigraphy of Southeastern New Mexico and Adjacent Parts of Western Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), p. 936.

bentonite. The log of this well, 35 miles distant from the Point, is in agreement with the outcrop section and confirms the belief that the lithologic relations which the formations bear to one another, as exposed in the western escarpment of the Guadalupe Mountains, hold in general throughout the reef trend. Fifteen miles northeast of Carls-

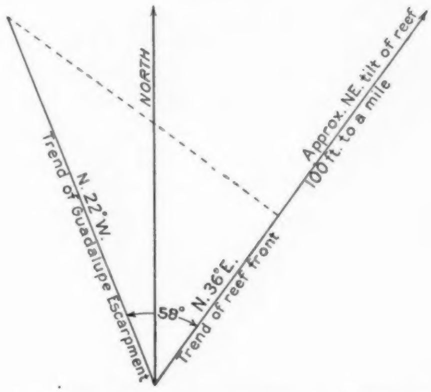

FIG. 16.—Diagram showing trend of the Guadalupe Escarpment and the reef front at the Point. The attitude of the bedding shown on the Guadalupe Escarpment is distorted as only sections taken perpendicular to the reef front (dashed line) provide a true cross section.

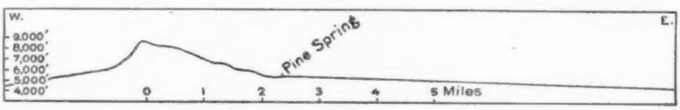

FIG. 17.—A west-east profile (drawn to scale) through the Point of the Guadalupes at Pine Spring. The steep east slope west of Pine Spring approximately represents the attitude of the reef front at the close of Delaware Mountain time.

bad or 27 miles in the same direction from the McIntyre well, the Getty-Dooley deep well No. 7 penetrated 2,700 feet of Carlsbad and Capitan limestones and 2,500 feet of sandstones of the Delaware Mountain formation. The position of both wells with respect to the reef is comparable but in the Getty area a much greater thickness of sediments accumulated, which suggests that this was a negative area.

CARLSBAD LIMESTONE

The name Carlsbad limestone came into field usage by petroleum geologists in the early 1920's for the limestones cropping out west of Carlsbad and later as a means of distinguishing the bedded from the massive limestones. It was introduced into the literature by Darton and Reeside[31] in 1926 as the Carlsbad limestone member of the Chupadera formation. This relationship, as previously noted, does not hold. The Carlsbad is an intimate associate of the Capitan, and was at one time referred to as the Carlsbad tongue[32] of the Capitan. The part of the Carlsbad limestone which caps western Azotea Mesa (Fig. 2) and overlies the Seven Rivers gypsiferous member of the Chalk Bluff is here given the name of Azotea tongue. Some field geologists prefer to consider the Carlsbad as a facies of the Capitan, and it is admittedly difficult to make a separation in the subsurface where diagnostic evidence does not appear in the cuttings. On the surface this difficulty is less real. Present knowledge of its thickness, areal extent, and lithology are such as to warrant its being designated a separate formation.

The Carlsbad limestone overlies and completely blankets the Capitan, except where faulting or erosion has exposed the latter. It is a bedded formation of three times the lateral extent of the Capitan. The Queen sandstone serves to separate this limestone from beds below that are very similar lithologically—the Dog Canyon. The eroded reef front between McKittrick and Double canyons shows distinctly the band of bedded Carlsbad limestone resting upon the massive and seemingly structureless Capitan. The reef limestones of the Barrera have been progressively stripped of overlying formations from west to east so that much of the Carlsbad is absent in the southwestern half of the Barrera. Northeast of Rattlesnake Canyon the Carlsbad covers in large part the Capitan limestone. The inclination of the Barrera to the northeast, descending from an elevation of 8,751 feet to 3,150 feet (an average gradient of 112 feet to the mile), carries the Capitan and Carlsbad limestones beneath younger rocks east of the Pecos.

The Carlsbad is a whitish, creamy to buff, and in some places a grayish dolomitic limestone. Locally it is pinkish to almost red in color and on close inspection is found to be composed of fragments of fossil shells of a small number of species. Fusulinids are abundant in the Carlsbad; some of the basal beds along the crest of the reef

[31] N. H. Darton and J. B. Reeside, Jr., "The Guadalupe Group," *Bull. Geol. Soc. America*, Vol. 37 (1926), p. 419.

[32] S. Spencer Nye, *op. cit.*, p. 44.

northeastward from the Peak are almost wholly composed of them. Texturally the limestone varies from a gritty granular form to one of lithographic fineness. Toward the back reef many beds and tongues of sandstone are included with fine stringers of shaly red sandstones and limestones and greenish shale. Some beds are thin and platy or

FIG. 18.—Pisolitic concretions from the Carlsbad limestone. Walnut Canyon, Carlsbad Caverns National Park, New Mexico. Size, —0.9. Note the bedding, and fragmental character of many of the pisolites.

even finely laminated. One of its most prominent features is the presence of zones of pisolitic concretions, some of whose individuals attain a diameter of two inches (Fig. 18). Algae (*Girvanella*) have been identified in these pisolites but there is no evidence to prove whether the algae are responsible for or merely accessory to the accumulation of calcium carbonate to form the pisolites.

In places the limestone bedding surfaces are characteristically covered with markings, some of which the writer interprets as ice-crystal impressions (Fig. 19).

The Carlsbad limestone is variable in thickness. The thin down-folded tongue exposed on the south side of the Barrera thickens by gradational replacement of the Capitan to 600–800 feet within a

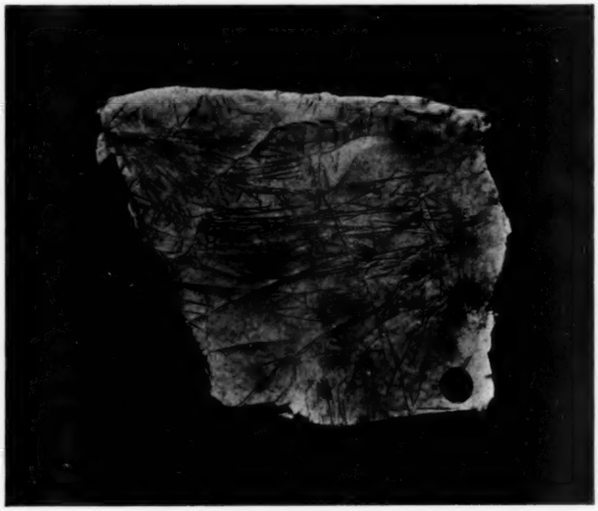

FIG. 19.—A slab of Carlsbad limestone covered with a network of ice crystal (?) marks.

short distance northward. Where it is seen to intergrade with the Seven Rivers, it abruptly thins from 300 to 50 feet.

FORMATIONS OF THE FORE-REEF ZONE

BONE SPRING LIMESTONE

Only the black limestone, the "Basal Black limestone" or "the lowest member of the Delaware Mountain formation," as it has previously been called, is represented on the surface in the fore-reef province. This formation was described by Blanchard and Davis[33] as the Bone Springs limestone in 1929, and derives its name from Bone Spring near the head of Bone Canyon, sometimes called Bone

[33] W. Grant Blanchard, Jr., and Morgan L. Davis, "Permian Stratigraphy and Structure of Parts of Southeastern New Mexico and Southwestern Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 961–64.

Spring Canyon, which is directly beneath the Peak on the west side of the Guadalupe Mountains. This limestone is crossed by the Carlsbad-El Paso highway at the foot of Guadalupe Canyon. Much of the lower portion of the formation is here concealed by bolson deposits and it is overlain by sandstones of the Delaware Mountain formation. The dip of the beds is to the south and the formation rises northward

FIG. 20.—Ripple marks (?) from the contact zone of the Castile anhydrite with the Lamar limestone. Carlsbad-El Paso highway between McKittrick and Bell canyons.

until 1,500 feet or more are exposed. It is then gradually replaced by the gray limestone in the reef zone. Though the Bone Spring formation is termed a limestone, much of it is a gray to black limy shale, in parts sandy. In the vicinity of Bone Spring Canyon (Fig. 14), large blocks of the dense, black, thin-bedded limestone are tilted at various low angles to each other, yet are an integral part of the formation. This structure is interpreted by the writer as the result of slumping caused by movement of the sea floor during deposition of the sediments.

The dense, black members of the Bone Spring are true limestones and break with conchoidal fracture, giving a strong petroliferous odor. The limestone is highly carbonaceous, but yields very little bituminous matter when digested with hydrochloric acid. The residue con-

tains extremely fine sharp sand grains, bryozoans, and sponge spicules. The bryozoan fossils are distinguishable in the residue by their rusty reddish color. Where less carbonaceous, the limestone is brownish to dark gray with some large nodular chert inclusions.

In 1921 to 1922 the N. B. Updike core test was drilled on the Williams Ranch 3 miles due south of the Point. It began approximately at the top of the Bone Spring limestone and was drilled to a total depth of 3,400 feet. The essential features of the core are given in the following abridgment of the driller's log.

Depth in Feet		*Thickness*	*Description*
From	*To*		
0	2,484	2,484	Gray limestone and shale
2,484	2,504	20	Fine-grained sandstone
2,504	2,524	20	Sandy limestone and shale
2,524	2,613	89	Gray limestone and shale with some black sandy shale
2,613	2,633	20	Fine gray sandstone with gray limestone bands
2,633	2,649	16	Sandy shale and gray limestone with chert
2,649	2,864	215	Gray limestone with black sandy shale
2,864	2,883	19	Honey-combed gray limestone with shale partings
2,883	2,919	36	Gray limestone with large fossils
2,919	2,948	29	Gray limestone with shale partings and conglomerate
2;948	3,051	103	Conglomerate
3,051	3,183	132	Gray and black limestones, conglomerates, and black sandy shales
3,183	3,304	121	Black limestone with partings of shale
3,304	3,351	47	Compact sandstone with shale
3,351	3,400	49	Cray limestone with shale bands

The Bone Spring limestone is possibly represented to a depth of 2,484 feet, for this portion of the core is a lithologic unit. A more critical determination of the section must await additional fossil or stratigraphic evidence from some other source in the area. From 2,484 feet to 3,183 feet the section includes sandstones and conglomerates. These conglomerates are of considerable interest and consist of well rounded limestone pebbles in a limestone matrix. They are suggestive of the Abo (Wolfcamp) and therefore are a part of the basal portion of the Permian. The Pennsylvanian therefore is represented by the remaining core below 3,183 feet. This evidence for correlation is admittedly weak and a more satisfactory solution of the problem awaits new data.

On the assumption that the base of the Permian lies within the sandy and conglomeratic zone between 2,500 and 3,000 feet in this core, the total thickness of Lower Permian rocks in the fore-reef area probably exceeds 3,000 feet. This 3,000 feet of Lower Permian (all

formations up to the top of the Bone Spring) added to 3,500–5,000 feet of Middle (Delaware Mountain formation) and 5,000 feet of Upper Permian (Castile, Salado, and Rustler), would give a total thickness of 11,500–13,000 feet in the fore-reef area.

DELAWARE MOUNTAIN FORMATION

Richardson[34] in 1904 first applied the name Delaware Mountain formation to the section of sandstone and black limestone below the Capitan limestone that is exposed on the western slope of the Guadalupe and Delaware mountains. This name is now restricted[35] to include only the sandstone, the black limestone of a different lithologic and faunal character being now known as the Bone Spring limestone. The Delaware Mountain formation is exposed on both flanks of the Delaware Mountains and for a short distance along the west side of the Guadalupe Mountains.

Girty's[36] Guadalupian fauna occurs in the Capitan limestone and in related formations of the reef and fore-reef zones that were formed during the Delaware Mountain epoch. Although he made some collections from the black limestone (Bone Spring), most of his material came from the higher sequence. The time interval of the Delaware Mountain formation is of interest because it marks the culmination of the Guadalupian fauna, after which representative life forms in the Permian were practically extinguished in the area discussed, and also because it was the time of greatest reef building around the margins of the Delaware basin.

At the beginning of Delaware Mountain time a basin, of slightly greater area than that now represented by the Capitan reef zone, was deepened. In this basin the Delaware Mountain sands were deposited, at first transgressing bed by bed upon the eroded margin of the basin and later interfingering with ingrowing limestone reefs until the basin had filled to a thickness of 2,500 feet. In the fore-deep before the reef front this thickness increased to 3,500 feet. Along with the sands were deposited beds of limestone. The Delaware Mountain formation may be divided into three parts, divisions which are not well marked within the basin but are representative of events that occurred about the rim. The lower sands of medium grain size overlap the Bone

[34] G. B. Richardson, "A Reconnaissance in Trans-Pecos Texas, North of Texas and Pacific Railway," *Univ. Texas Mineral Survey Bull. 9* (1904), p. 38.

[35] P. B. King, "Permian Stratigraphy of Trans-Pecos Texas," *Bull. Geol. Soc. America*, Vol. 45 (1934), p. 756.

[36] G. H. Girty, "The Guadalupian Fauna," *U. S. Geol. Survey Prof. Paper 58* (1908); "The Guadalupian Fauna and New Stratigraphic Evidence," *New York Acad. Sci.*, Vol. 19, No. 6, Pt. 1 (1909), pp. 135–47.

Spring with a basal conglomerate that spread about the rim. When the basin was about half full of sands, limestone deposition commenced about the rim and the Dog Canyon limestones were built up, grading laterally into sands of the middle Delaware Mountain. The completion of the Dog Canyon stage of development was soon followed by the more perfect reef growth of the Capitan, which interfingered with the very fine sands of the upper Delaware Mountain.

The Delaware Mountain formation is a dark gray to buff sandstone. The fineness of grain of the sandstones is a notable feature. They grade upward from a medium-grained sandstone to a siltstone and, where well cemented by calcium carbonate, lose completely their appearance of being a sandstone. Dark gray to black limestone beds and lenses occupy portions of the formation. Both the black limestones and dark-banded sandstones are carbonaceous; the banding, though similar in type, is far less prominent than that in the Castile. This fine banding which the Upper Permian deposits display so magnificently is also present in deposits throughout the Permian. Many of the limestones and sandy limestones are so formed but the banded structure is rarely evident. The more resistant limestones form benches and cap the mesas in the outcrops of the Delaware Mountain. On the slopes below the Point the writer has observed fragments of a very fine-grained, green, chert-like rock in the float. This comes from a horizon a few hundred feet below the base of the Capitan and, according to P. B. King, can be traced for many miles along the west-facing scarp. Samples submitted by King to C. S. Ross, of the United States Geological Survey, were determined to contain undoubted fragments of volcanic material and were classified as a bentonite. This bentonite is closely allied stratigraphically with bentonites that occur in the Maljamar area at a depth of 2,500 feet or more in the Chalk Bluff formation.

Within the Delaware basin the top of the Delaware Mountain formation is marked by a black calcareous bed that has proved to be a useful correlation unit. It has a remarkably uniform thickness of about 25 feet and is readily recognized because its dominant black color contrasts with the surrounding lighter-colored sediments. Within the basin this unit is a dark carbonaceous, highly calcareous sandstone or arenaceous limestone, but as the basin rim is approached the bituminous content decreases, the calcium carbonate increases, and the rock grades into a definite limestone. It finally becomes a pale gray limestone at the base of the Barrera Escarpment, and is in places overlain by additional Delaware Mountain beds of sandstone and limestone, of variable thickness up to probably 35 feet. To this unit is

here given the name Lamar limestone member of the Delaware Mountain formation. The Lamar limestone is named for Lamar Canyon, southeast of the Guadalupe Mountains. The type locality is selected as the escarpment north of Lamar Canyon where the canyon is crossed by the Western Gas Company's pipe line. This is about 15 miles due east of the Point. This limestone was previously referred to by Blanchard and Davis[37] as the "Frijole," from Frijole Post Office, Texas. Frijole Post Office lies on a similar dark limestone lower in the section and is many miles away from the Lamar member. In view of King's recent detailed mapping of the Guadalupe Quadrangle and his intention to name other interfingering members and to avoid possible confusion, the name "Frijole" is not used here (Figs. 4 and 21).

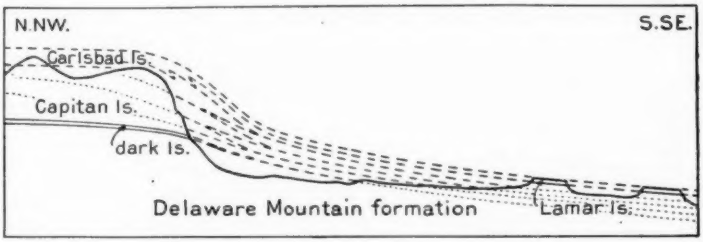

FIG. 21.—Diagram of the Point of the Guadalupes showing restoration of eroded beds of Carlsbad, Capitan, and Delaware Mountain formations and the relationship which the Lamar bears to the Carlsbad limestone.

An examination of well cuttings from the Stanolind Oil and Gas Co's C. A. Duncan well No. 1, drilled in Sec. 30, T. 21 S., R. 30, E., Eddy County, New Mexico (elevation, 3,320 feet), the results of which are given on pages 876–77, serves to show the character of the Lamar member of the Delaware basin as it appears in well samples. The Lamar is a very sandy limestone, generally 25–30 feet thick, and black from a strong organic impregnation. The sand grains are rarely visible in the rock because of their extreme fineness. The Lamar represents a stage when carbonate deposition temporarily exceeded the accumulation of sand, an interpretation that applies to many other limestone members of the Delaware Mountain. The sands appear to have been supplied to this basin almost continuously and their deposition was at times punctuated by the arrival of increased amounts of carbonates and organic residue from the reef mass.

[37] W. Grant Blanchard, Jr., and Morgan L. Davis, *op. cit.*, p. 973.

POST-DELAWARE MOUNTAIN FORMATIONS

With the close of Lamar (=upper part of Carlsbad) deposition came an important change in Permian conditions, the end of reef building here and of a normal marine sea in the Delaware basin. The subsequent deposits, of a different type, consist of the Castile anhydrite, the Salado halite, and the Rustler formation, which complete the Permian sequence.[38]

The cause of this sudden cessation of Delaware Mountain sedimentation can only be conjectured. Too little is known of the connection this basin had with the more open sea to the southwest in trans-Pecos Texas and Mexico. The cause may have been a structural movement which restricted the shallow southwestern entrance of the basin or shifted by uplift the continental shelf connection with the

PARTIAL LOG OF THE DUNCAN WELL NO. 1
STANOLIND OIL AND GAS CO.
SEC. 30, T. 21 S., R. 30 E., EDDY COUNTY, NEW MEXICO

Formations	*Subdivisions*	*Depth and Thickness*	*Description*
Castile anhydrite		3,350–3,380	White anhydrite—very calcareous. Anhydrite crystals clear. Calcite crystals are either large or occur in clusters. Scattering of well-rounded quartz grains—1.5 mm.—minute pinkish to reddish clay pellets. Estimated anhydrite-calcite ratio—60 to 40
		3,380–3,410	Whitish to grayish anhydrite—calcareous, otherwise same as above. Darker color of sample probably due to a slight increase in organic content
		3,410–3,451	Whitish anhydrite—calcareous. Anhydrite 75 per cent or more of sample. Calcite a pale brownish color. Banding indicated. Rounded quartz grains and clay pellets present
		3,451–3,455	Brown anhydrite—calcareous. After treatment with HCl yields abundant organic residue. Quartz grains and clay pellets
		3,455–3,459	White anhydrite with some brown anhydrite and brown calcite and black limy sandstone. Few fragments of pale buff limestone. Red clay pellets

[38] W. B. Lang, "Upper Permian Formations of Delaware Basin of Texas and New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19 (1935), pp. 262–70. The Salado halite or the upper salt series is the same as the unit which has been called "upper Castile" by some subsurface geologists. See, for example, L. D. Cartwright, "Transverse Section of Permian Basin, West Texas and Southeast New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14 (1930), p. 980. The Pierce Canyon redbeds are now placed in the Triassic and may be related to the Bissett.

PARTIAL LOG OF THE DUNCAN WELL NO. 1 (*Continued*)

Formations	*Subdivisions*		*Depth and Thickness*		*Description*
Delaware Mountain formation	Zone of calcareous cementation		12 feet	3,459–3,463	Dark sandy limestone. Percentage of sand and lime about equal. Quartz grains sharp, clear, and coarser than usual. Octahedrons of pyrite
				3,463–3,471	Calcareous sandstone becoming increasingly darker with depth. Calcite cement—25 per cent. Effervesces violently with HCl. Pyrite
		Lamar limestone member	24 feet	3,471–3,495	Black sandstone—highly calcareous. Organic inclusions oriented like biotite flakes in a schist. Pyrite. Organic inclusions unaffected by HCl. Sand grains clean up on treatment with hot H_2SO_4 and $K_2Cr_2O_7$
			10 feet	3,495–3,505	Grayish to brownish limestone—50 per cent brownish limestone, 25 per cent white limestone, 25 per cent black sandstone. A few fragments of this brown limestone are in preceding sample
			5 feet	3,505–3,510	Pale grayish to buff sandstone. Fragments appear very much like a fine-textured limestone but treatment with acid reveals the matrix to be an extremely fine-grained (1/10 mm.) sand of sharp clear quartz
			Weakly cemented	3,510–3,537	Pale gray sandstone. Calcareous cement decreases with depth. Quartz grains are sharp, fine, and clear
				3,537–3,545	Gray sandstone. Quartz grains slightly coarser, sharp and clear. So weakly cemented that the grains fall apart on standing in water
			Cement free	3,545–3,570	Buff sandstone—sharp, clear grains practically free of calcareous cement. A few quartz grains show pale, red and yellow colored inclusions and some are milky. 95 per cent of quartz grains are crystal clear. Grain size—1/5 to 1/10 mm. Buff color probably due to a very small amount of hydrous iron

open sea far southwestward into Mexico, for the conditions, which had prevailed to a more limited degree in the back-reef area in Delaware Mountain time, subsequently advanced into the Delaware basin. Though the amount of movement was probably slight, the effect on sedimentation was great. It restricted circulation of the sea water but did not close connection with the sea. Marine waters continued to advance into the basin. They were shortly altered in composition by partial evaporation and by commingling with more concentrated waters of earlier additions to the basin. As the saturation points for the various salts were reached, they were successively precipitated

to accumulate in zones forming more or less segregated deposits of anhydrite, halite, or other salts. This structural change which limited circulation of the sea water, gave to the climatic factor the opportunity to impress its influence on the type of subsequent deposition. The importance of organisms as agents of deposition ceased and chemical processes became supreme. In the Delaware basin above the Delaware Mountain formation, with the exception of clastic sandstones and shales and the thin Rustler dolomitic limestones, 5,000 feet of sediments are virtually products of chemical precipitation.

The change from Delaware Mountain to Castile sedimentation requires further study and interpretation. The Castile filled this basin in front of the reef and in places may have overlapped the rim. It is therefore restricted geographically to the Delaware basin. The contour of the bottom of the basin was mildly warped as were also the Castile sediments. The deepest portion of this basin is east of the Pecos River, where the Castile deposits are more than 2,500 feet thick and contain the most halite. Above the Castile lies the Salado halite, which is 1,000 to 1,500 feet thick and not only covers the Delaware basin but extends northward and eastward without interruption. The Salado is in turn overlain by the Rustler formation.

CORRELATION

Correlation of the Permian formations of the Pecos Valley with those on the eastern side of the Permian basin in Texas and southwestern Oklahoma must rest upon subsurface data, for there are no connecting outcrops between the eastern and western sides of the basin. Distances from western outcrops to those on the east are as much as 200 miles and nowhere less than 100 miles. Between these outcrops color and lithology change and in some of the formations fossils are completely absent. Because redbeds, anhydrites, and sandstones possess little to distinguish them, their correlation is a hazardous and difficult task. The following table is offered as a tentative correlation of the back-reef formations with those of Texas and Oklahoma classifications.

Two of the units correlate with relative certainty—the San Andres with the Blaine and the Chalk Bluff with the Whitehorse and associated rocks. They contain (as shown on p. 879) equivalent time intervals but their boundaries are probably not exactly contemporaneous. The San Angelo sandstone and the Hondo occupy the same stratigraphic position, but of the many sandstones in the Yeso it is not known which one or ones may be the true equivalent of the San Angelo. The few wells that have been drilled into the deeper lying

A TENTATIVE CORRELATION OF THE BACK-REEF FORMATIONS OF THE PECOS VALLEY WITH THOSE OF TEXAS AND OKLAHOMA

*Pecos Valley of New Mexico**			*Connection beneath Llano Estacado*	*Texas*†	*Oklahoma*‡
	Rustler Salado				
Castile					
Delaware Mountain	Carlsbad, Three Twins Azotea Capitan, Seven Rivers Queen Dog Canyon	Chalk Bluff	←——→	Quartermaster Alibates Cloud Chief Whitehorse	Quartermaster Day Creek Whitehorse (Cloud Chief, Rush Springs, Marlow)
		San Andres	←——→	Blaine	Dog Creek Blaine Chickasha
Bone Spring		Hondo			
(Wolfcamp‖Hueco)		Yeso Abo		San Angelo Clear Fork Wichita	Duncan (Hennessey) (Garber-Wellington)

* "U. S. Geological Survey classification," this paper.
† "Geology of Texas," *Univ. of Texas Bull.*, Vol. 1, No. 3232 (1932).
‡ Noel Evans, "Stratigraphy of Permian Beds of Northwestern Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 4 (1931), pp. 405–39.

rocks, the Yeso and Abo, are widely spaced and do not afford evidence for precise correlation.

The Castile hardly extends beyond the basin rim. This may be caused by non-deposition or erosion. It is rather strange that 2,500 feet of sediments could have accumulated in the Delaware basin during Castile time, without some counterpart being deposited about the marginal areas, unless the sea-level was below the rim, in which case shore-line phenomena which have not yet been recognized should be in evidence. There are probably far more hiatuses in the Permian than have been suspected or determined, and much local erosion.

The Salado thins northward, as also does the Rustler. On the west side of the basin east of the Pecos both the Salado and the Rustler were truncated before deposition of the Triassic. Adams[39] considers that these formations are similarly truncated in the north Texas area, and this relationship most likely holds beneath all the Llano Estacado in New Mexico, although the writer has not had opportunity to extend a precise correlation to this region. Thus, according to Adams, the Quartermaster, if present in southeast New Mexico, would be equivalent to beds near the top of the Chalk Bluff.

Part II

FACTORS CONTROLLING PERMIAN SEDIMENTATION

The basic explanation of Permian basin geology is to be found in the interpretation of its structure. Structural movements were of paramount importance in controlling the location and type of sediment deposited. Other factors were contributory but less fundamental. Warping of the epicontinental floor expanded and contracted the basins of deposition, provided catchments for sediments, shifted the zone of contact of the marine and saline waters, either invited or scattered the fauna as the environment dictated, and provided realms for an excess of chemical precipitation. Those processes and conditions which, from the nature of the sediments, it is believed were operative, are here tabulated in the order of their apparent importance.

1. Gradual negative movement, plus minor differential variations during the Permian
2. Progressive sedimentation maintaining shallow water
3. An arid climate persisting throughout the Permian in the Southwest

[39] J. E. Adams, "Upper Permian Stratigraphy of West Texas Permian Basin," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 7 (1935), pp. 1010–22.

SUBSIDENCE

The Permian rocks of the region record a period of subsidence, a gradual retreat of the Pennsylvanian sea to which the Permian fell heir. The average rate of sinking was greater in the south than in the northern portion of the basin and caused a progressive overlap of the

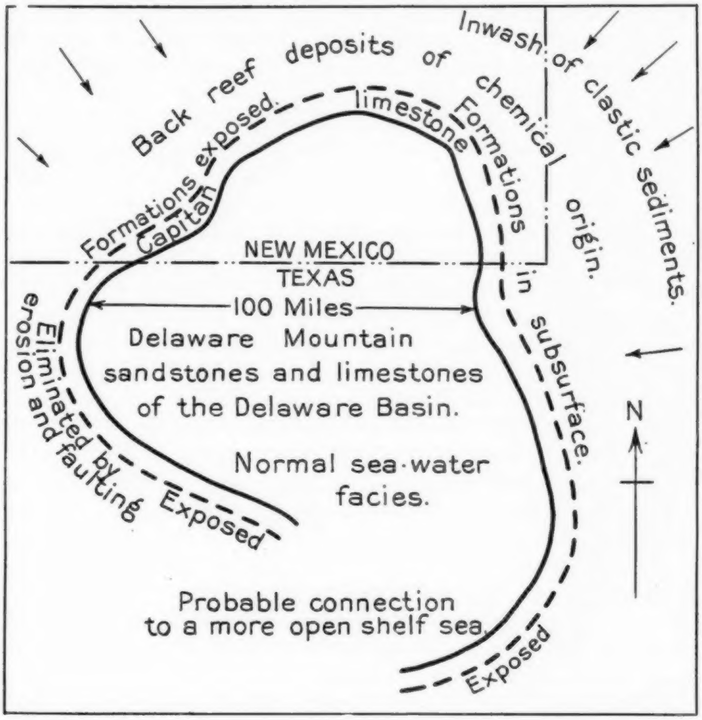

FIG. 22.—A diagram of the Delaware basin during formation of the Capitan limestone, showing the positions of the related types of the sediments and the character of the waters in which they were deposited. The present position of the reef limestones is also indicated.

red clastic sediments on the gray limestones and intermediate deposits. Greater thicknesses of sediments also accumulated in the south. The rate of deposition (or supply of sediments) gradually came to exceed the rate of basin sinking. The greatest period of quiescence, as represented by a sediment, occurred during the Castile, for it contains fewer clastics per unit volume of material than any other

Permian formation. The basin responded to further movement, affording a better connection with the ocean during the Rustler, when a marine sea from the southwest made two brief transgressions. The Permian epoch came to a close under conditions similar to those that persisted during Castile time. During the Triassic further warpings of the floor occurred, but it was then very near to or above sea-level and the basin was covered with terrestrial sediments from the rising highlands. The Triassic waters were brackish and deposited red sandy shales that bear no apparent evidence of life.

DEPTH OF THE NERITIC SEAS

Shallow water appears to have persisted throughout the lifetime and the extent of this Permian epicontinental sea. Except possibly during the later period of reef building and the transition to the Castile, it seems doubtful that the water in the back-reef of this broad flat sea was ever deeper than a few hundred feet and far more often it may have been less than 100 feet. The deepening of a depression by subsidence was progressively followed by in-filling which maintained the sinking floor in shoal-water position. Irrespective of the type of sediment, ripple marks, rill marks, cross bedding, channel scouring, drying cracks, mudballs, autoclastic breccias, intraformational conglomerates, erosion intervals, oölites, pisolites, frosted dune sands, ice-crystal markings (Figs. 19 and 20), etc., are found in them, individually or collectively. Some of these features required an actual intermittent emergence of the surface on which they were formed. Some geologists have postulated a depth of water in the Delaware basin, toward the end of Delaware Mountain time during the building of the Capitan reef, greater than the present height of the reef limestone, or 1,000–2,000 feet (Fig. 17). Conflicting evidence, however, appears at the base of the reef in the form of current channeling. Ripple marks of short wave length are present, and Crandall[40] reports finding what he considered to be cracks formed by drying. Though ripple marks can not be classed as convincing evidence, they are at least suggestive evidence of shallow water.

Most of the fore-reef formations contain deposits which consist of a succession of very minute layers, and diastems within them are not immediately in evidence. Quiet water is essential for their deposition; to have remained undisturbed, their position of accumulation must have been below wave base. Granting this point, the next question is to what depth did wave base extend in the Delaware basin in Permian time? This is a factor that is dependent upon the intensity

[40] K. H. Crandall, *op. cit.*, p. 943.

and duration of atmospheric movement. The nature of the deposits suggests a quiet atmospheric condition and thus favors a shallow wave base. The bulk of the water-borne clastic material is very fine, which indicates weak agents of transportation. More critical data are necessary before a proper evaluation of these factors is possible. Whatever may have been the average depth of the waters during the Permian of this area, it is evident that very little clastic material entered the basin. What did come appears to have arrived from the sandy back-reef bars, through low swales in the reef crest. The cause for this restriction to a minimum of the transportation of clastic sediments to the basin may have been due to the further reduction of rainfall and tributary drainage from marginal lands.

CLIMATE

A sediment is made up of one or more elements. Where more than one element is involved the sediment represents the sum of elements contributed from different sources. The element that becomes the dominant component of a sediment is dependent in large measure on the relative activity of the contributing agents. Climate is thus one of the factors that controls the type of sediment deposited. When anhydrite or halite beds attain a dominant position in a sediment, even to the exclusion of all others, a hot dry climate is to be inferred and the agent is that of chemical precipitation. Anhydrite, halite, and the redbeds are the most characteristic sediments of the Permian basin.

The climatic factor probably also reversed the normal direction of flow of the waters to be expected in a partially enclosed epicontinental sea. In a temperate climate the abundance of rainfall produces an outflow of drainage from the land to the sea. Though tidal currents may carry marine waters into broad estuaries, the net effect is certain to be an outward circulation, bringing a contribution to the sea. But under very arid conditions, the balance of flow is inward. The atmosphere contributes little and absorbs much moisture, not only from the water surface but also from the land. Thus, under proper conditions, a marginal brackish-water zone is developed near the land, which may be separated from the marine water by a highly saline zone where the chemical precipitation of sediments is most active. This condition probably existed throughout Permian time, sometimes only locally, but it apparently became more general and intense during the final stages, the indraft of marine water from the open sea having reached a maximum during Salado time.

Normal marine water apparently occupied the broad open shelf

that faced the ocean. As these waters were drawn inward over an undulate floor they commingled with other waters that had previously entered and become concentrated to greater salinity, lost their fauna, and precipitated much of their salts. It probably was along such trends of increasing salinity that limestones accumulated, perhaps from both organic and inorganic causes. The excessive growth of limestone reefs may have further restricted circulation and contributed to a more rapid concentration of those waters advancing into the back-reef zone. The most favorable life environment in the Permian seas was apparently upon these marginal limestone areas that bordered the areas where conditions for life were intolerable. There, in this most favorable environment, the waters were warm, shallow, and sunlit. Micro-organisms must have been plentiful. Accidental migration of these organisms into the more saline zone killed them off. A plentiful food supply, both living and dead, was thus provided for other organisms living within this border area and a cycle of abundant organic activity was thus maintained. It is along this life zone that the great fields of petroleum production are now distributed. Beyond the limestone zone, the saline concentration of the waters was intolerable for life. The fauna advanced with every favorable incursion of congenial waters and was forced to retreat, if not killed off, by a return of waters of a higher salinity than could be endured. Farther inward, beyond the zone of interfingering limestones and sandstones, developed the chemical and clastic zones wherein the dominance of sandstone and shale or of anhydrite and halite depended on the relative activity of detrital or chemical deposition.

THE DISTRIBUTION OF PERMIAN SALINE DEPOSITS

It appears that throughout Permian time, some part of the basin area always contained waters of more than normal salinity. All the Permian major stratigraphic horizons contain halite or anhydrite at some locality and are associated with redbeds. Figure 23 has been constructed to show the vertical continuity of saline basins in the Permian and the general horizontal southwestward shift of these basins in each successive formation. A graphic attempt has been made to evaluate the comparative importance of these deposits in terms of the volume of halite and anhydrite present. Limestones generally preceded and redbeds followed their shift southwestward. This succession is illustrative of the tilt of the epicontinental embayment toward the southwest and the gradual withdrawal of the seas in that direction.

ZONES OF SEDIMENTATION AND THEIR RELATION TO COLOR

Color is one of the most obvious characteristics of a formation. In many places Permian formations change in color as they change in composition laterally, a variation that may be assigned to a transition from one realm of deposition to another. In the southern Permian basin this relationship is strikingly portrayed, and possibly may be

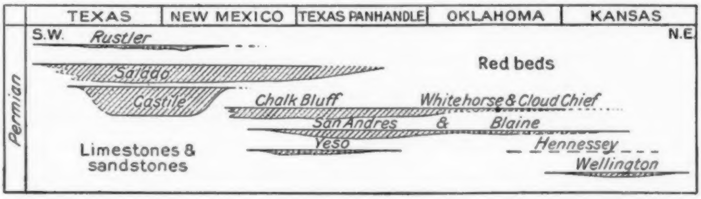

FIG. 23.—A schematic diagram of the Permian basin from Kansas to West Texas showing the shift southwestward of the basins of saline deposition during Permian time. The relative position, extent, and volume of the salines for each formation is represented by the cross-hatched areas.

applied equally well to other basin deposits of a similar origin. A color scale of black, gray, buff, white, and red is suggested as representative of the sedimentary transition occurring from more nearly normal sea-water deposits inward, through the shallow saline water zone, to the realm of chemical deposits and terrestrial clastics.

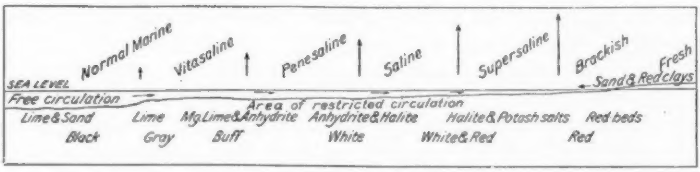

FIG. 24.—A theoretical conception of a Permian basin sea, showing the zones of increasing salinity as the landward side is approached, the dominant sediment deposited in each zone, and its general color. Horizontal arrows indicate direction of flow of water. Length of vertical arrows suggests the rate of evaporation.

From field evidence it is apparent to the writer that the deposits formed in an embayed epicontinental sea under the influence of an arid climate are subject to classification into zones in accordance with the character of the water in which they were deposited. Waters of a salinity greater than normal sea water have a more critical effect upon the character of the deposits and upon life environments than have those waters of a lower salinity. Within these different zones certain types of deposits are found, and they are generally of a color

that is distinctive of a particular zone. Thus color, ordinarily a character of secondary importance, may possibly be useful as an indicator of the probable environment of deposition. To know the environment of deposition of a sediment is essential for an accurate paleogeographic interpretation.

Although the increase in salinity is a more or less gradual process, four distinct stages of concentration are evident. These stages which represent the zones of deposition are here given names in order to express simply the relationship which any saline water or deposit bears to the basin of deposition. They are, in the order of increasing salinity: the vitasaline, penesaline, saline, and supersaline stages.

Those Permian deposits that possess a fauna and physical attributes indicative of accumulation in normal sea water of moderate depth are generally limestones, shales, or sandstones of a black or dark gray color. These are classified in Table I as normal marine deposits of a normal marine sea.

The gray to buff limestones generally show evidence of shallow-water deposition. Most of them are dolomitic. Fauna and flora are abundant, far more so than in the black limestones, except where this zone is transitional to the next stage. Though a gradual increase in salinity occurred across this zone, life was abundant and, owing to this increased salinity and possible rise in temperature of the water, the saturation point for the lime content was attained and the lime thus may have been ready for precipitation either directly or through organic agencies. This is the *vitasaline* stage or the reef zone, where, despite a slight increase in salinity, life flourished in abundance.

The next stage includes the many very short lithologic transitions that occur in the back reef, and a transition from a favorable life environment to one apparently totally devoid of life—from organic to dominately chemical precipitates. Here the buff to whitish colors predominate, and buff and gray dolomitic limestones, gray-buff, pink, and white sandstones are in association with white anhydrite. This is the *penesaline* stage, and is best represented by anhydrite.

With further increase in salinity, halite is precipitated. Where halite displaces anhydrite as the dominant representative of the sediments the *saline* stage is attained. Polyhalite in the form of blebs, stringers, and beds, and red and buff clastics are commonly associated here with halite. The colors of the beds are pale gray to white, becoming reddish. The deposits are wholly without direct evidence of life.

With still greater concentration, the potash salts become prominent and the color probably reddens. Redbeds with gray-green and

black shale are common associates. This is the final or *supersaline* stage, which is very seldom attained, for dilution of the mother liquor or a resolution of these highly soluble salts is more likely to occur before they can be covered and preserved.

Behind the supersaline stage or, in its absence, bordering a pre-

TABLE I

DOMINANT COLOR OF DEPOSITS AND SALINITY OF THE WATER IN AN EPICONTINENTAL SEA DEPOSITING SALINE SEDIMENTS

Geographic Position of the Water	*Character of Water*	*Type of Sediments Deposited*	*Representative Sediment*	*Dominant Color*
Open ocean	*Marine water*—Salinity the average of that of ocean water of the particular geologic period	Calcareous muds, oozes, meteoritic and volcanic material	Radiolarian cherts, etc.	
Marginal portion of epicontinental sea	*Normal marine*—Sufficient depth of water and circulation to maintain normal condition	Dark limestone, sandstone, and shale	Limestones and shales	Black to gray
Reef zone	*Vitasaline*—Shallowing sea floor. Constricted circulation. Salinity increasing above normal. Organic life abundant but dangerously near intolerable conditions	Limestones and sandstones. Limestones predominantly organic	Reef limestones, sandy limestones, and dolomitic limestones	Gray to buff
Back-reef zone	*Penesaline*—Concentration too great to sustain organisms	Chemical deposits: dolomitic limestone and anhydrite. Sandstone	Anhydrite	Buff to white
Shallow inland lobe of epicontinental sea	*Saline*—Volume of evaporation maintains a balance with indraft of concentrating waters so that sodium chloride precipitates out as the representative deposit. Most of the calcium sulphate has been precipitated in the penesaline zone	Anhydrite, halite, and polyhalite. Red shale	Halite	White to red
Shallow marginal pockets of the saline phase	*Supersaline*—A stage of concentration seldom attained	Halite with potassium-magnesium salts. Greenish and black shales. Magnesite	Potash salts	White to red. Varicolored
Transition zone of the fresh to brackish surface drainage with any of the above zones. Probably not existent when supersaline stage is reached	*Brackish*—Salinity less than that of normal sea water or of different composition than that of a concentrated marine water	Red shales and sandstones	Redbeds	Red, brown to purplish
Marginal land areas. Volume of land drainage probably inversely proportioned to salinity of marginal embayed waters	*Fresh water*	Sands and silts in transit		

vious stage, is the marginal or brackish-water zone where the salinity has been reduced by tributary terrestrial drainage. Here the color of the sediments is more likely to be red or buff from an abundant inwash of red shale or sand.

No Permian deposit apparently shows the complete series of stages, but some formations represent a number of them. Only the Salado is so far known to have attained in part the supersaline stage; it otherwise represents the saline stage throughout most of its extent. On the northeast, where it should grade into redbeds, this tendency is indicated. On the south, in trans-Pecos Texas, it should become more anhydritic and subsequently dolomitic. The Tessey limestone is considered by some to be in part the southern phase of the Salado.[41] The Castile and Rustler are anomalous in that their changes in character appear to be greater westward rather than southwestward. The Delaware Mountain and related formations of the back reef provide a fairly complete series of deposits representative of the various stages of concentration and associated color sequence.

It should be borne in mind that this outline applies only to the Permian basin or to those deposits having a similar mode of origin. Both saline deposits and redbeds may be accounted for by other processes and for them such a schematic relationship may not be applicable.

ORIGIN OF THE PERMIAN SANDS

Most of the Permian formations are sandy, in fact far more so than appearances indicate. The sands either take the form of distinct beds or are admixed with other sediments. One feature worthy of note is that the sand grains throughout the Permian are notably fine and sharp. Rounded, frosted, or coarse grains of sand are the exception and therefore have been found useful in lithologic correlation. However, heavy-mineral determinations made in 1927 of sandstones taken from various horizons in the Permian showed little indication of possessing distinguishing characteristics sufficient to provide a satisfactory aid to correlation.

The greatest accumulation of sand appears to have taken place during Middle Permian time when the sand bodies incorporated in the Delaware Mountain and Chalk Bluff formations were deposited contemporaneously in different areas. The two different areas of sedimentation were separated by a belt in which reef limestones were formed (Fig. 22). The Delaware Mountain, the Chalk Bluff, and the reef limestones are of the same age.

[41] J. E. Adams, *op. cit.*, p. 1019.

The problem of the source of the sands is not convincingly answered by present evidence, though the data seem to suggest a certain trend which, if capable of support by additional facts, may lead to a solution. There is very little if any difference between the sands of the Delaware Mountain and the Chalk Bluff formations. The more one studies the lithology and stratigraphy of the reef area the less one is convinced that the reef limestones acted as more than temporary barriers to the migration of the sands. Both sides of the reef limestones are bordered by sandstones and in middle Delaware Mountain time the sandstones extended across the reef zone from back reef to fore reef. Only during the very rapid building of the Capitan reef was there what appears to have been a temporary shut-off of sand migration when numerous tongues of sand accumulated in the Carlsbad behind the Capitan reef crest. Nor is it certain that at all places about the reef, sandstone beds may not extend through the reef—in fact the Three Twins member may be seen to come within a quarter

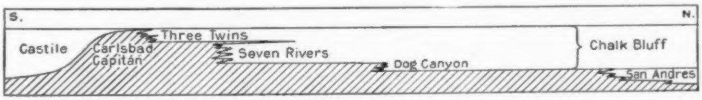

FIG. 25.—A diagrammatic sketch to show the progressive advance of the back-reef deposits of sandstone, anhydrite, halite, and redbeds toward the reef zone. The cross-hatched area represents the reef and fore-reef deposits of limestone and sandstone.

of a mile of the reef front and what is still more suggestive is the presence in the lower portion of the Castile of the same type of frosted sand grains as occur in the Chalk Bluff (Fig. 25). These and other factors to be mentioned lead the writer to believe that much if not all of the sand of the Delaware basin originated from sources beyond the back-reef area.

The most outstanding point in favor of the shifting of sediments southwestward is the very evident and constant progression of the zones of sedimentation southwestward with ascent of the stratigraphic column (Figs. 23 and 25). Intimately associated with the sands are the redbeds. They point back to a source in the general northeastward direction. The redbeds as such approach but do not enter the reef zone. Indeed the writer has never observed evidence of redbeds in the fore-reef zone. Redbeds are therefore here considered representative of back-reef conditions.

Some believe that the sands of the Delaware basin were brought in by marine waters from an outside source. This is possible but not probable. It is evident from the structure of the reef that such a

source, which under this premise might have contributed to the upper sands of the basin, could not by any means have supplied the sandstone fingers in the Carlsbad. The similarity of the sands above and below the Capitan reef argues, rather, in favor of a common source. Differences where shown by these sandstones lie chiefly in the character and degree of cementation.

In early Permian time local highland areas furnished abundant sediments, but they were soon drowned in their own and other debris. The Amarillo-Wichita and ancestral Rocky Mountain highlands ceased to exist as such, but their burial did not serve to interrupt the inflow of clastics that continued to arrive in the Permian basin throughout Permian time and became associated with the chemical precipitates. Sand and redbeds constituted the bulk of the clastics.

Where, therefore, can one look for a satisfactory source of all this material? Opinion is not unanimous as to the environment under which red clays develop, but a humid climate is generally regarded as the most favorable. At least the red clays now forming most abundantly are in hot, humid countries of relatively low altitude. The climate of the region of the Permian basin and of the contiguous area was not then suited to the generation of red clays according to this hypothesis. Also, it was a receiving, not a contributing, area. To supply the volume and kind of clastic material incorporated in the Permian deposits of the Permian basin, one or more areas of considerable extent lying in a humid belt previously subjected to a protracted period of weathering and during Permian time in the process of slow, continuous elevation, is necessary to satisfy the more acceptable hypotheses involved in this still vague concept. In a search for such areas, Appalachia as well as Llanoria are the only sources which seem to be adequate to satisfy the requirements. The Permian deposits of Iowa, Illinois, and West Virginia suggest a far closer approach of sedimentation in Permian time to Appalachia than might otherwise be thought likely. There is also some question whether or not Llanoria was sufficiently beyond the arid climatic realm to provide the proper type of sediments. The red Pennsylvanian rocks of Oklahoma and Texas suggest a close association with an arid environment which would prohibit the generation of laterites. It is postulated that with the elevation of Appalachia the saprolitic residue was gradually shifted westward from the zone of origin to the arid zone of preservation of the red aluminates. So long as the waters of deposition were concentrated salines, that is, without life, the red color of the clays was retained. Where these originally red clays passed beyond the reef into the organic realm of more normal sea water and better cir-

culation, they lost their red color, and became black or gray. The ferric iron which causes the red color probably changed to a ferrous carbonate or sulphide and some of it was removed in solution. Reworking of the clays by organisms with the addition of their carbon residues was probably responsible for much of the black to gray color that these clays assumed. During Delaware Mountain time comparatively little clay made the transit of the reef and the waters undoubtedly were fairly clear. The top currents bore inward the required balance to supply that lost through evaporation and the bulk of the material for chemical deposition. Tidal action and such outward bottom currents as may have existed served to work the sediments basinward.

STRUCTURE AND REEF GROWTH

The most important belt of structural movement in the southern Permian basin from the standpoint of influence upon sedimentation is that defined by the reef zone. The margin of the Delaware basin of San Andres time was considerably north of the present boundary defined by the front of the Capitan limestone. Progressive growth inward into the Delaware basin occurred in consequence of the greater rate of sinking of this basin with respect to the whole Permian basin and resulted in a reduction of the marginal limit. Within this zone the greatest amount of sedimentary gradation and interfingering took place, and the development of intra-formational conglomerates, slumping, erosion gaps, coarse cross bedding, and reef structure. The last is the most notable feature of this belt (Fig. 5).

The San Andres limestone is interpreted as a bedded reef limestone. It does not present reef structure so strikingly as does the Hess limestone member of the Leonard formation in the Glass Mountains.[42] The belt of gray San Andres limestone spreads over a wide area. It occupies the same relative position to other sediments as do the younger reefs, for it grades northward into anhydrites and redbeds. Stratigraphically above it are the bedded, sandy, Dog Canyon limestones, which increase in thickness and terminate southward in more massive limestones, which in turn grade into sandstones of the middle part of the Delaware Mountain (Figs. 9 and 14). Farther north this series also has a phase of saline water deposits. As the process of reef building continued about the flexed rim of the basin it became, with each successive growth, more intensive. The bedded type of limestone gave way to the massive limestones on the crests

[42] P. B. King, "Limestone Reefs in the Leonard and Hess Formations of Trans-Pecos Texas," *Amer. Jour. Sci.*, 5th ser., Vol. 24 (November, 1932), pp. 337-54.

of the reefs and during Capitan time deposition of limestone was very rapid. Some of this lime must have been of chemical origin. The Capitan and Carlsbad limestones compose the third reef and mark the culmination of reef growth on the northern rim of the basin. These limestones are similarly associated with saline back-reef deposits, but they extend farther into the basin, for reef growth was then more extensive. The massive limestones, which are inconspicuous in the San Andres and only partially developed in the Dog Canyon, are magnificently represented in the Capitan. Such a succession of reef growths could only have evolved upon the inclined rim of a sinking floor. This rate of sinking must have slackened in the final period of reef growth, permitting a further encroachment of the back-reef sediments upon the reef area and a choking of further reef growth. This may have been the cause for the termination of Permian reef development, for the saline zone which had persisted in the back reef during Capitan time subsequently shifted into the Delaware basin in Castile time (Fig. 25).

The reef structure in cross section is strikingly similar to a delta deposit. The Carlsbad and Capitan limestones and the upper beds of the Delaware Mountain formation are in their relationship analogous to the top-set, fore-set, and bottom-set beds (Fig. 5 and Fig. 28). They are, however, different in composition and source of material, for the delta is composed entirely of clastics derived from the land, whereas the Permian reef proper, which consists of fore-set beds, is composed of organic and chemical precipitates from the sea. One feature that distinguishes these reefs from the typical present-day fringing reefs is that the lagoonal phase or back reef was a realm of concentrated sea waters evolved under the influence of an arid climate.

SUBSEQUENT DEFORMATION

With the passing of the reef-building period there ensued movement tending to depress the Delaware basin side of the reef. Because of the fact that the beds on the reef face had an original basinward dip, and because the axis of folding was not always in the same relative position within the reef zone, the amount of this movement is difficult to determine. The postulated later flexing may be related to joints now found running parallel to the reef front and to local minor faults occurring along the same trend.

The Carlsbad limestone is arched along the Barrera, and the crest of this arch follows Guadalupe Ridge (Fig. 4). The dip of the beds on the southeastern slope is gentle, but in the vicinity of Walnut

FIG. 26.—A southward view from the Peak down upon the Point and Salt Basin. The system of parallel faults may be seen on the west slope of the Delaware Mountains.

FIG. 27.—A view northeastward along the reef front and across the mouth of Pine Canyon showing the reef beds of the Capitan limestone descending to meet the sandstones of the Delaware Mountain formation. The distant profile is made by the top beds of the reef and basin deposits of the close of Delaware Mountain time.

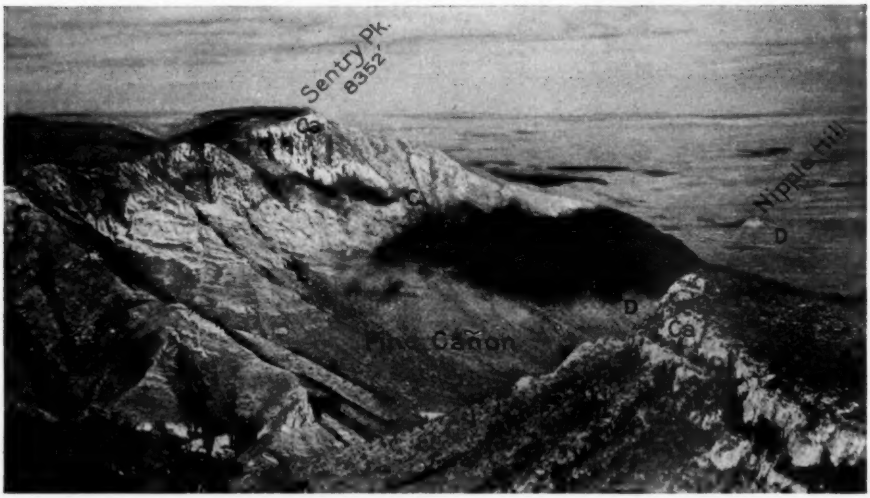

FIG. 28.—A view northeastward from the top of the Peak, showing the gradation of the reef limestones of the Capitan into the Delaware Mountain formation (D). The Carlsbad limestone (Ca) here is seen capping the Capitan limestone (C).

FIG. 29.—A view north-northeastward from the Peak and across Pine Canyon, showing a section of the reef limestones of the Capitan (C). The Carlsbad limestone (Ca) caps the Mesa. This view is a continuation of Figure 28 (to the left).

Canyon, where these limestones are well exposed, they may be seen at the crest of the escarpment to increase in dip and to plunge beneath the pediment of Black River Valley. These beds contain many pisolitic zones, and the pisolites were chipped and broken repeatedly by wave action and repaired by additional coatings of calcium carbonate during formation (Fig. 18). They are in beds now tilted at an angle too steep to retain free spheres subject to wave action.

Later movement of the reef front is also indicated by variations in the thickness of deposits that overlie the reef limestones. Not all lithologic variations now observed in these beds are necessarily effects produced at the time of deposition but some may be in part caused by removal of considerable thicknesses by solution.

Minor structural deformation of the Salado halite is indicated by drill cores and by the underground workings of the potash mines. The potash (sylvite) beds are irregular where they overlie the reef, but farther south in the basin they remain relatively constant in thickness and composition. Movement apparently has caused flowage of the salts, more especially the sylvite, which resulted in minor warping. Asymmetrical folds with axes parallel to the reef crest have developed and a tendency for the sylvite to concentrate at points of less stress is indicated.[43] Apparently the overload has been insufficient to induce incipient doming.

TILTING OF THE DELAWARE BASIN

The western flank of the southern Permian basin syncline is made up of two monoclines, the Sacramento monocline, which dips toward the east and is bounded on the west by a north-south trending fault, and the Guadalupe monocline, which dips toward the northeast and is also similarly bounded by a fault zone that trends more northwest to southeast. The Sacramento monocline bears upon it the back-reef deposits and the Guadalupe monocline contains essentially the deposits of the reef and the Delaware basin. The Sacramento Mountains and adjacent ranges north of them occupy the uptilted western edge of the Sacramento monocline, which is bordered on the west by the deep graben of Tularosa basin. The Guadalupe and Delaware mountains occupy a similar position upon the Guadalupe monocline and are likewise bordered westward by the graben of Salt basin. In the Sacramento Mountains gentle folding preceded faulting, but the

[43] The suggested tendency of sylvite to flow more readily than halite may explain why sylvite is seldom found in the Gulf Coast salt domes. Assuming that sylvite is present in the salts at depth where a dome is forming, it would tend to migrate upward with the head of the dome and would, on reaching the zone of circulating ground water, be the first to disappear beneath the cap.

Guadalupe fault zone appears to have originated upon initial tilting of the monocline. The maximum vertical displacement represented by each of these fault zones exceeds 5,000 feet and the monoclines mark the beginning, toward the west, of the basin-and-range type of structure.

SUBSEQUENT GEOLOGIC HISTORY

The direction of the dip of these two monoclines and the trend of the fault lines that border them represent two major physiographic controls in this part of the Southwest. The influence of these two monoclines is directly reflected by the trend of the Pecos River and its tributaries. The drainage pattern imposed upon the limestones of the Guadalupe Mountains is of post-Cretaceous origin, as a result of the eastward and northeastward tilt of the monoclines. These are the consequent streams that have been superimposed through the higher, softer rocks onto the more resistant limestones of the Barrera. Dark Canyon is a typical example, for the upper part of its course lies along the crest of, and its lower course cuts directly across, the Barrera (Fig. 2). Drainage dependent on faulting follows in general a north-south direction and parallels the trends of the scarps, grabens, and synclines. The Pecos Valley, though not of fault origin, is a result of the monoclinal tilting that produced the faults on the west and developed the drainage as it now exists in Dog Canyon. Adjustment of drainage to later movements and to the variations in attitude and hardness of the deeper beds as exposed by erosion have resulted in stream capture, especially along the Barrera, where tributaries of Black River have intercepted consequent drainage or are about to do so. It is a notable fact that canyons entering the Barrera west of Dark Canyon have only western tributary canyons. The greater amount of displacement expressed in the Guadalupe fault system probably occurred during the Pliocene and Pleistocene. Faulting has beheaded the Guadalupe and Pine Canyon drainage (Fig. 14) and in Dog Canyon only incipient adjustment has occurred along the scarp since hinge faulting took place.

There is no apparent evidence of tilting prior to the close of reef building in Permian time, but during Castile and Salado times faint suggestions of an inceptive uplift of the southern Rocky Mountains are indicated. As there are no Upper Permian formations west of the longitude of the Guadalupe Mountains, evidence of their westward extent is wanting, and an interpretation of events must rest entirely on speculation. The Rustler, however, in Reeves and Culberson counties, Texas, lies first on a truncated surface of the Salado and,

farther west, on an apparently slightly beveled surface of the Castile. Erosion rather than solution appears to have been the cause.

On the Sacramento monocline west of the Pecos River, the younger Permian deposits have been stripped off by erosion so that the two sides of the valley present an entirely different appearance. The eastern side is composed essentially of redbeds; the western side is an exposure of limestone.

TABLE II

COMPARISON OF THE ROCKS EXPOSED ON THE WEST AND EAST SIDES OF THE PECOS RIVER IN THE VICINITY OF ARTESIA NEW MEXICO

West Side of Pecos Valley or Sacramento Cuesta		*East Side of Pecos Valley to the Llano Estacado*	
Cretaceous	Sierra Blanca basin (Capitan Mountains)		
Triassic		Triassic	
		Rustler	poor exposures
		Salado	not exposed
		Castile	not exposed
Chalk Bluff (remnants)		Chalk Bluff	exposed
San Andres		San Andres	In subsurface
Hondo		Hondo	
Yeso		Yeso	
Abo	In subsurface or on the bajada slope	Abo	
Magdalena		Magdalena	

This leaves, on the western side, a stratigraphic gap between the Chalk Bluff, or upper Middle Permian, and the Triassic. Apparently, east of the Grand Canyon region, where the Moenkopi is found lying on the Kaibab, there are no sedimentary rocks to fill this gap. During part of the intervening period this area was, in all probability, a highland. Though the Triassic sediments of the Permian basin indicate a general uplift with reference to sea-level, relative sinking continued here, for the thickest Triassic deposits are found along the axial trend of the syncline. Also the Triassic, which rests on the Rustler east of the Pecos Valley, is reported lying on the San Andres in the Sierra Blanca basin, a relationship that implies further eastward tilting of the two monoclines. This is also suggested by the arrangement of the deposits of the Comanche seas which appear to encircle the Guadalupe-Sacramento area, the basal sandstones ascending stratigraphically as they approach this region from the south and east. The Trinity and Fredericksburg seas filled in the margins about these highs, but in Washita time sediments may not have been deposited over the higher elevations. As little structural change is evident, the

Upper Cretaceous seas probably transgressed the more even floor of Comanche deposits without difficulty.

Such deformations as had occurred were broad gentle features but with the close of the Cretaceous began a series of events including igneous intrusion, faulting, and tilting that established the pattern and created trend lines that later periods of movement have served only to intensify. In addition to the pronounced movement of the monoclines the area became involved in a regional uplift. The earlier part of the Tertiary appears to have been chiefly an epoch of erosion, but in the Pliocene rapid erosion was accompanied by development of enormous inter-montane pediments and the formation of the Tertiary deposits of the High Plains east of the Rocky Mountains. The Quaternary period was also a time of great activity and the results are of many kinds. The processes of faulting and tilting continued, pediments were dissected and built. Lake, eolian, and stream-gravel deposits were formed and caliche caps evolved. Probably more than half the present tilt of the Guadalupe and Sacramento monoclines was acquired during the late Miocene and Pliocene. This movement continued through the Quaternary and may still be an active process today.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 21, NO. 7 (JULY, 1937), PP. 899-913, 6 FIGS.

UPPER CRETACEOUS OF ROCKY MOUNTAIN AREA[1]

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ABSTRACT

The Upper Cretaceous series is the most widespread and the thickest in the Rocky Mountain area and more work has been done on it and more published than on any other series, but the literature is full of conflicting local names and is very confusing. The Upper Cretaceous sediments were eroded from a western land mass and deposited in a vast marine basin. Thick sandstones on the west side grade eastward into shales and finally even into limestones. In the west five main sandstone units can be differentiated with four intervening shale bodies and these have been given different names in different places. In the eastern area the series is largely shale and has been subdivided by paleontologic methods and by using the few limestones, but the two sets of subdivisions do not match. It is suggested that the entire problem be reviewed, group names given the main western sandstone and shale units for use through the Rocky Mountains, and many names eliminated. A conference of those in authority and those most interested and best informed might well be held to arrange such a simplification of the Upper Cretaceous nomenclature.

The Upper Cretaceous series in the Rocky Mountain area is several thousand feet thick and covers a vast area from Utah to Minnesota and from New Mexico far into Canada (Fig. 1). It consists mostly of dark marine shale, but in the western and west-central areas of its outcrop contains many sandstones, and on the eastern edge a few thin limestones. It is much more important than the series of any other geologic period because it covers the greatest area, is thickest, and has been the most important in production of coal, gas, and oil, not excluding the Jurassic Sundance formation, which has the spotlight at this moment. These Upper Cretaceous rocks have been mapped and studied by geologists for more than 60 years and more is known and published about them than about any other series. It might be assumed that the story was told and nothing more need be written, but after working continuously 14 years in the Rocky Mountains, the writer believes the Upper Cretaceous is very confusing and full of unnecessary duplicating and overlapping geologic names. The suggestion is offered that the time has come when the entire Upper Cretaceous series should be reviewed and a system of names chosen to fit genetic conditions and mappable lithologic units. Since there is a recognized procedure for the change of geologic names, and since it should be a matter of discussion and con-

[1] Published by permission of Stanolind Oil and Gas Company, Tulsa, Oklahoma. Manuscript received, April 15, 1937.

[2] Division Geologist, Stanolind Oil and Gas Company.

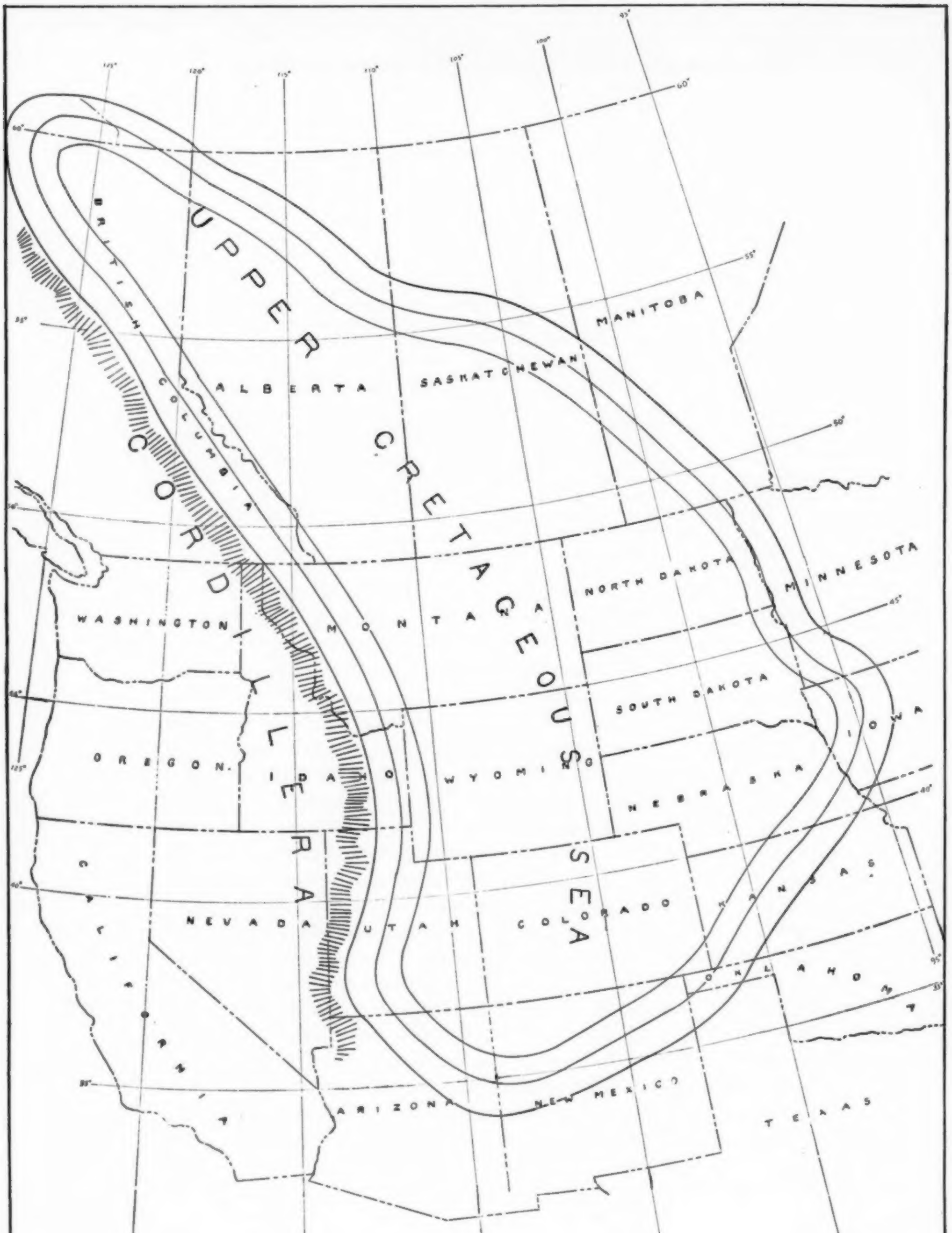

FIG. 1.—Map of Rocky Mountain and Great Plains areas to show extent of Upper Cretaceous sea in the United States and Canada and the eastern edge of the Cordillera.

sideration by those familiar with the problem, the writer will not here advocate any definite changes, but will suggest many that could be made advantageously in the near future. In any event, it does not seem likely that any new names will be needed, since old names will more than suffice, but with revision of the limits of some.

The geology of the Rocky Mountain Upper Cretaceous is relatively simple. The Cordilleran land mass had risen during Jurassic time in western Utah, Idaho, British Columbia, and adjacent areas, and sedimentary material eroded from it was washed into the surrounding country. In late Jurassic and all of Lower Cretaceous time, such sediments were spread over a great flood plain east of the Cordillera in the present Rocky Mountain area. At the beginning of the Upper Cretaceous, the sea spread over the flood plain east of the Cordillera and formed a marine basin extending from Utah 900 miles eastward to Iowa and Minnesota, and from New Mexico and Arizona on the south far into Canada and Alaska on the north. The total area covered in the United States and Canada exceeds 1,700,000 square miles. The sea may have extended much farther toward the southeast, east, and north, and later erosion may have removed any Cretaceous deposits.

The greatest uplift of the Cordillera and also its most easterly point were apparently close to southeastern Idaho and northeastern Utah. East of that point the Upper Cretaceous sediments are 8,000–10,000 feet thick and include much sandstone and coarser material, but throughout most of the Rocky Mountain area the marine basin was filled to a depth of 4,000–5,000 feet. A rough estimate of the total sediments eroded from the Cordillera and deposited on its eastern side during the Upper Cretaceous alone is 1,200,000 cubic miles in the United States and Canada and it appears that very little of this could have come from sources in other directions.

Under these conditions, streams and rivers flowing east on the Cordillera dropped their boulders and coarse gravels at or near the shore line to form conglomerates; swept the sands farther east to build great deltas and to be carried and spread by sea currents into sheets of sandstone; and washed muds still farther east to settle and form the present thick marine shales. In the quiet water toward the eastern side, a few limestones were deposited, but none extended very far toward the west. Thus, at any one time, conglomerate might be forming in the west, while, progressively farther east, sandstone, shale, and limestone were accumulating.

Geologic and climatic conditions on the Cordilleran land mass were not constant and at three intervals during Upper Cretaceous

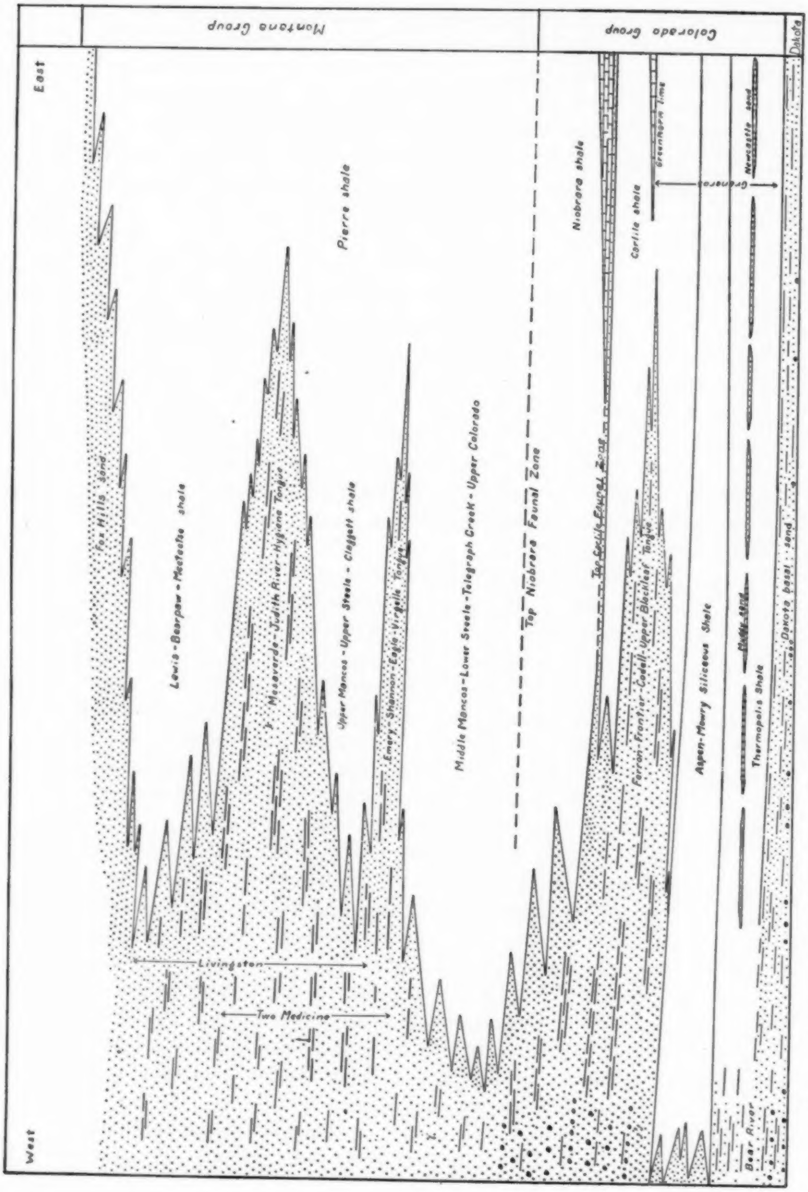

FIG. 2.—Cross section of Upper Cretaceous from west to east, to show relation of western tongues of sandstone and eastern limestones and faunal divisions.

time sandy material was carried much farther east than during intervening periods, and formed three great tongues or wedges of sandstone projected into the shale body, thinning irregularly and disappearing eastward. These sandstone tongues contained commercial coal beds and were mapped extensively in the western parts of New Mexico, Colorado, Wyoming, and Montana, and the sandstones and intervening shales were given other formation names. At that time, little was known about the regional geologic picture, and, since distances were great in the Rocky Mountains, long-range correlations could not safely be made, and different local formation names were used in each locality. Most of those names are still in use.

Several hundred miles east in the open plains states, other geologists were mapping the Upper Cretaceous where it contained no sandstone, except the basal Dakota, and, since their only mappable beds were limestones, they had to use the limestones or faunal zones to subdivide the shales. This resulted in additional different sets of names for rocks of the same age, but of different composition. For many years this caused no confusion, but finally the intervening areas were mapped and old formation names carried into other districts, where they conflicted with and overlapped other formations.

Figure 3 is a correlation chart, which shows most, but not all of the geologic names that are still in good usage in the Rocky Mountains. As an example of the number of names in use, one can begin at a certain shale horizon in the Mancos shale in western Colorado, and, by following it north, find oneself progressively in the Hillard shale, the Baxter shale, the Steele shale, the Cody shale, then in Montana the Claggett shale, and in Canada the Pakowki shale. The writer contends that many of these names are unnecessary and confusing and that the time has come to review the Upper Cretaceous and simplify its nomenclature. This statement, the writer believes, will have the support of oil geologists from California and the Mid-Continent, who are now entering the Rocky Mountain area.

Granted that it should be simplified, many names eliminated, and some revised, this may be difficult to accomplish and there will be many different plans. To be correctly done, it must follow the rules for *Classification and Nomenclature of Rock Units*,[3] in which the statement is made "that lithologic constitution is now accepted as the controlling basis of subdivision, partly because of its usefulness and immediate availability in mapping, and partly because of its genetic and economic significance." On that basis, lithologic constitution should be used as far as possible to subdivide the Upper

[3] G. H. Ashley and others, *Bull. Geol. Soc. America*, Vol. 44 (1933), pp. 423-59.

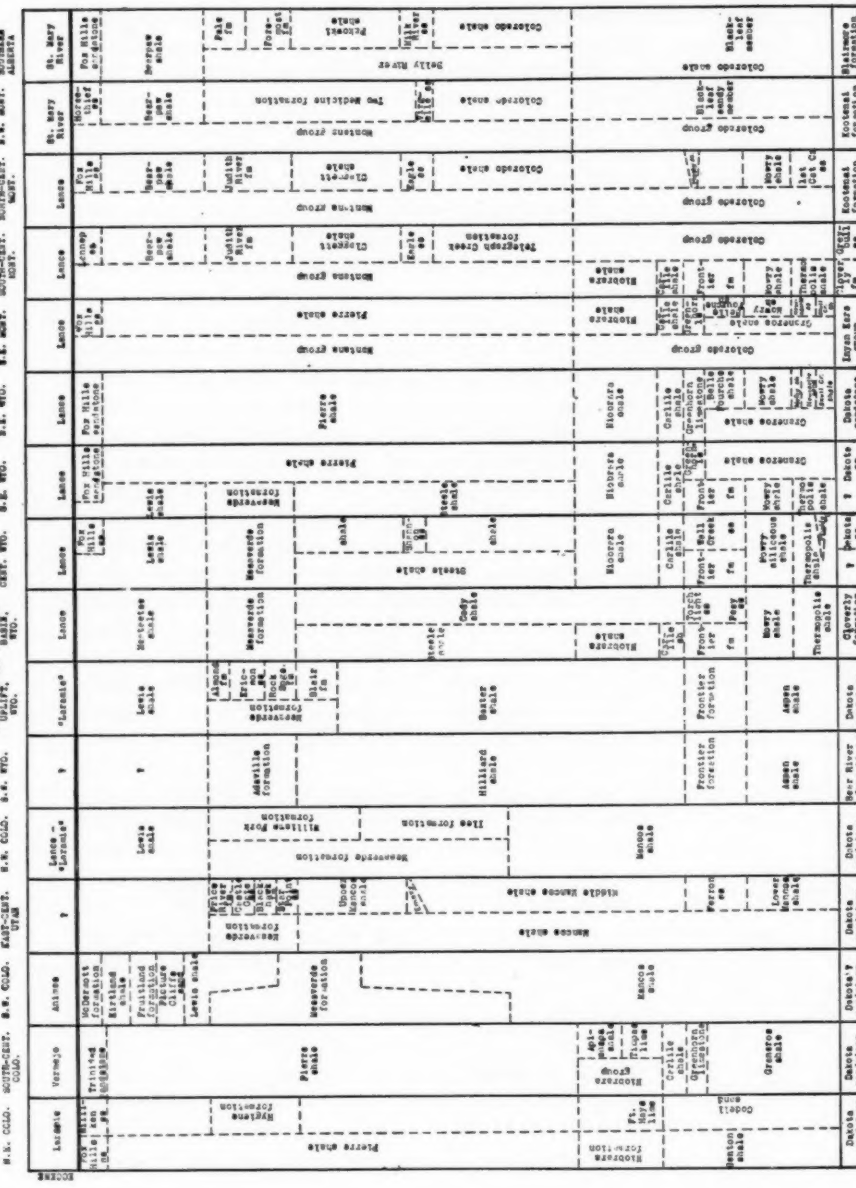

FIG. 3.—Correlation chart of Upper Cretaceous formations in Rocky Mountain area.

Cretaceous, which means that the alternating sandstone and shale units of the western half of the Rocky Mountain area should be a controlling factor and their limits should be carried east as far as possible.

The writer's work throughout the region leads him to believe that in the western part the Upper Cretaceous can best be divided into five sandstone units with four intervening shale bodies and it will briefly be described here on that basis (Fig. 2). The five sandstone units are a basal sandstone that covers the entire area, three large tongues or wedges that are thick near their source in the west and thin to a knife edge and vanish toward the east, and an upper sandstone that apparently covered all the region and marked the end of marine conditions. The four intervening shale units of the west thicken as the sandstones thin toward the east and merge as the sandstones disappear, and finally in the eastern part are divided by only two limestones.

The lowest sandstone is the basal sand of the encroaching Upper Cretaceous sea, which reworked materials left on the Jurassic and Lower Cretaceous flood plain and redeposited them in an irregular group of sandstones, sandy shales, and shales. This zone is 100–300 feet in thickness and in most places contains two, three, or even four or five individual sandstones, which are local lenses of limited extent, and not unbroken sheet sands. Throughout the Rocky Mountains this zone of sandy material is everywhere found at the base of the marine section, but one individual basal Dakota sand does not exist, as generally believed. The usual practice is to select three sandstones in this zone and, if the lowest one is coarse and conglomeratic, to give it the name Lakota[4] or an equivalent name and to regard it as Lower Cretaceous, to call the middle sandstone the true Dakota[5] if it has dark shale above it, and to give the highest one the name Muddy[6] or an equivalent name. The entire group has been given the name of Cloverly[7] but that is little used, and the writer suggests that the name Dakota be broadened to include the group, that some local names be used for individual sandstones, and that many of the local names be dropped as unnecessary and confusing. This group is a

[4] N. H. Darton, "Geology and Underground Water Resources of the Central Great Plains," *U. S. Geol. Survey Prof. Paper 32* (1905), p. 34.

[5] F. B. Meek and F. V. Hayden, "Description of New Lower Silurian (Primordial), Jurassic, Cretaceous and Tertiary Fossils Collected in Nebraska Territory," *Philadelphia Acad. Nat. Sci. Proc. 1861*, Vol. 13, pp. 417–42.

[6] W. T. Lee, "Continuity of Some Oil-Bearing Sands of Colorado and Wyoming," *U. S. Geol. Survey Bull. 751* (1923), pp. 1–22.

[7] N. H. Darton, "Comparison of the Stratigraphy of the Black Hills, Big Horn Mountains and Rocky Mountain Front Range," *Geol. Soc. Amer. Bull.*, Vol. 15 (1904), p. 398.

FIG. 3.—Correlation chart of Upper Cretaceous formations in Rocky Mountain area.

transition from Lower Cretaceous into Upper Cretaceous and contains varying amounts of each, but is a genetic unit.

The next sandstone body (Fig. 4) is the lowest of the three sandstone tongues and is here assumed to include the Frontier[8] formation of Wyoming, the Ferron[9] of Utah, the upper part of the Blackleaf[10] member of the Colorado group in Montana, and the thin Codell[11]

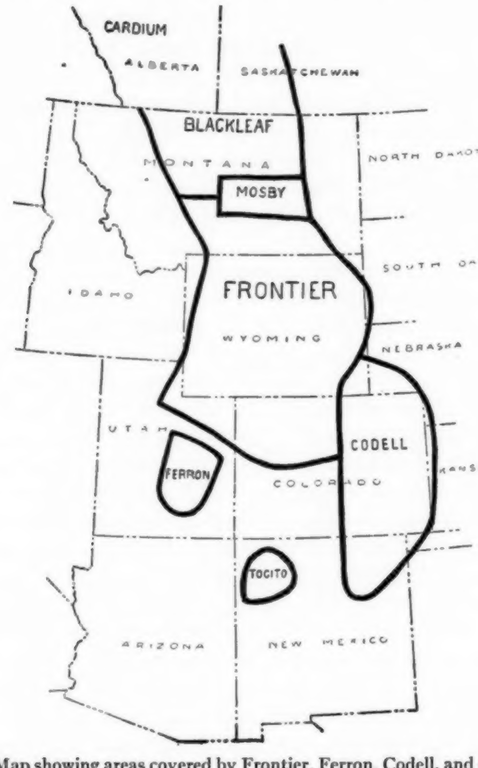

FIG. 4.—Map showing areas covered by Frontier, Ferron, Codell, and other sandstones believed to be parts of lowest sandstone tongue.

[8] W. C. Knight, *Bull. Geol. Soc. Amer.*, Vol. 13 (1903), pp. 542–44.

[9] C. T. Lupton, "The Geology and Coal Resources of Castle Valley, Utah," *U. S. Geol. Survey Bull. 628* (1916).

[10] Eugene Stebinger, "Oil and Gas Geology of the Birch Creek-River Area, Northwestern Montana," *U. S. Geol. Survey Bull. 691* (1919), pp. 149–84.

[11] N. W. Bass, "Geologic Investigations in Western Kansas," *Kansas State Geol. Survey Bull. 11* (1926), p. 28.

sandstone of eastern Colorado. It is not generally agreed that these are all parts of the same body of sandstone; many are not ready to correlate them. The Blackleaf probably includes some beds older than the Frontier, as well as equivalent beds. Nevertheless, they were all deposited during an interval of Upper Cretaceous time, when renewed uplift of the Cordillera or increased erosion supplied

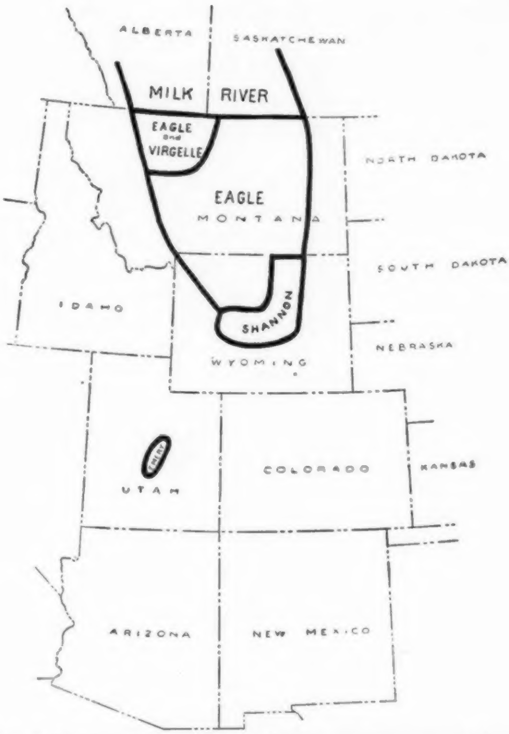

FIG. 5.—Map showing areas covered by Eagle, Shannon, Emery and other sandstones believed to be parts of the middle sandstone tongue.

more sand that was carried farther east into the sea. The Frontier sandstones were deposited on a great delta and its sandy beds thin to the north, east and south. The Ferron formation could have been entirely continuous with the Frontier or may have been deposited independently by another river. The Blackleaf is separate, but is probably on the outer edge of another delta that can not now be

seen. The writer argues that it is reasonable to assume that the same conditions caused the Cordilleran rivers to be more active at the same time and that these sandy beds will finally be proved to be of the same age. He suggests that work be done to determine this and if they are all as close to one age as he believes, that they be placed in one group, which might well be named the Frontier. Such a name would indicate that sandstone found at about that horizon is part of a great tongue that may be thousands of feet thick in eastern Utah but may thin to 5 feet in eastern Colorado, and will not leave the literature full of many apparently unrelated formations. As previously stated, such a group can be subdivided in any locality into mappable formations and members, but many conflicting names should be eliminated.

The next sandstone group (Fig. 2) includes the Emery[12] sandstone of Utah, the Shannon[13] of Wyoming, and the Eagle[14] and Virgelle[15] of Montana. It is not as thick as the other two sandstone wedges, but is prominent in central Wyoming and Montana and has been mapped throughout large areas. There is less occasion for argument about this group, because the Shannon has already been traced into the Eagle, the Virgelle is known to be the lower part of the Eagle, and the Emery also has an Eagle fauna. The writer believes it would be helpful if geologists would admit that the exact limits of such a sandstone tongue vary from place to place and that varying transition zones occur between it and the adjacent shale, and agree on one name for this tongue throughout the entire area. The writer would suggest here that, if it can be done, the names Emery, Shannon, and some others be dropped, that the group be named the Eagle, and that the Virgelle be called the Lower Eagle.

The third and upper sandstone tongue (Fig. 2) includes the Mesaverde[16] of Colorado and Wyoming, the Judith River[17] of Montana, and the Hygiene[18] of eastern Colorado. At the present time the

[12] F. R. Clark, "The Geology and Coal Resources of the Sunnyside, Wellington and Castlegate Quadrangles, Utah," *U. S. Geol. Survey Bull. 793* (1928), pp. 10–14.

[13] C. H. Wegemann, "The Salt Creek Oil Field, Wyoming," *U. S. Geol. Survey Bull. 452* (1911), pp. 37–83.

[14] W. H. Weed, "Geology of the Fort Benton Quadrangle, Montana," *U. S. Geol. Survey, Geol. Atlas, Folio 55*.

[15] Eugene Stebinger, "Anticlines in the Blackfeet Indian Reservation, Montana," *U. S. Geol. Survey Bull. 641-C* (1917).

[16] W. H. Holmes, "Geological Report on the San Juan District, Colorado," *U. S. Geol. and Geog. Survey Terr., Ninth Ann. Rept. for 1875* (1877), Pl. 35.

[17] T. W. Stanton and J. B. Hatcher, "Geology and Paleontology of the Judith River Beds," *U. S. Geol. Survey Bull. 257* (1905).

[18] N. M. Fenneman, "Geology of the Boulder District, Colorado," *U. S. Geol. Survey Bull. 265* (1905), pp. 31–33.

Mesaverde is considered a group and has been frequently described as a great tongue of sandstone that thins eastward,[19] but no serious effort has been made to ascertain whether its area can be enlarged. If present knowledge or additional information shows that the sandstones and sandy shales of the Hygiene formation in eastern Colorado

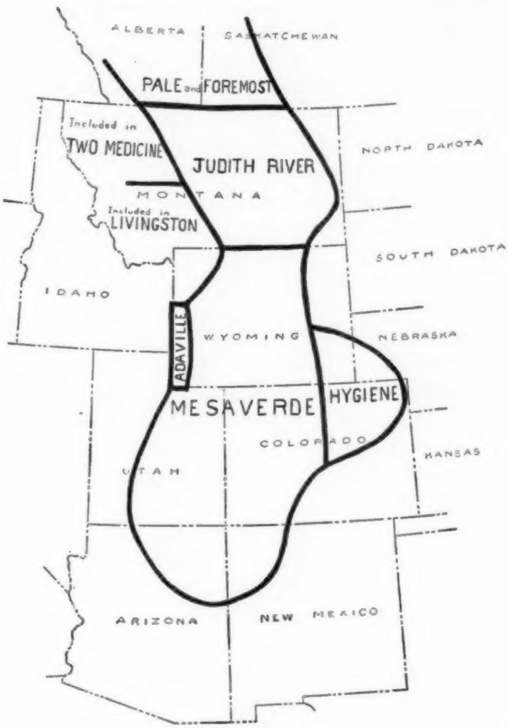

FIG. 6.—Map showing areas covered by Mesaverde, Hygiene, and Judith River formations, believed to be parts of upper sandstone tongue.

pass into the zone of the Mesaverde, it should not be difficult to persuade the geologists in eastern Colorado to forget the name Hygiene and use Mesaverde. The same is true of the Judith River in Montana, and the writer believes that all geologists except a few, who have lived most of their lives in that state, think Mesaverde

[19] Edmund M. Spieker and John B. Reeside, Jr., "Cretaceous and Tertiary Formations of the Wasatch Plateau, Utah," *Geol. Soc. Amer.*, Vol. 36 (1925), pp. 435–54.

when they say Judith River. Of course, the writer believes all this group could best be named the Mesaverde.

The uppermost sandstone (Fig. 2) is not as important in this discussion, since it is recognized generally as one bed or group, the first of the great non-marine series that followed the withdrawal of the Upper Cretaceous sea. It is called the Fox Hills[5] in most places and that name probably could be extended advantageously and such local names as Horsethief,[20] Milliken,[21] Trinidad,[22] and Lennep[23] be dropped.

This discussion of the sandstone tongues has not yet considered the areas in the west where the sandstones merge together and no intervening shale units exist. Theoretically that condition exists all along the eastern side of the Cordillera, but later uplift and erosion have removed that belt in most places. In south-central Montana the Upper Cretaceous above the Eagle sandstone contains much volcanic material, and, since the different sandstone and shale units can not be mapped, the beds are all grouped into the Livingston[24] formation. In northwestern Montana, for the same reason, inability to map them separately, the formations between the Eagle and the Bearpaw are called Two Medicine.[25] The same conditions may be found elsewhere as other inaccessible western areas are mapped and as more work is done on the non-marine beds above the marine Cretaceous in western Wyoming, Idaho, and Utah. In those areas suitable names must be used, but that should not prevent simplification elsewhere.

Returning to the central area, the division of the shales is more difficult than that of the sandstones, because all the shale units merge together eastward and throughout large areas have long been divided by paleontologic methods and by the few thin limestones that extend but short distances into the sandstone country. The well known faunal zones of the east side do not coincide at all with the sandstone tongues but cut across their boundary lines. Thus, the Codell sand-

[20] Eugene Stebinger, "The Montana Group of Northwestern Montana," *U. S. Geol. Survey Prof. Paper 90* (1914), p. 62.

[21] Junius Henderson, "The Cretaceous Formations of Northeastern Colorado," *Colorado Geol. Survey Bull. 19* (1920), pp. 22–23.

[22] R. C. Hills, "Elmoro, Colorado," *U. S. Geol. Survey Geol. Atlas, Folio 58* (1899).

[23] R. W. Stone and W. R. Calvert, "Stratigraphic Relations of the Livingston Formation of Montana," *Econ. Geol.*, Vol. 5 (1910), p. 746.

[24] J. P. Iddings and W. H. Weed, *U. S. Geol. Survey Geol. Atlas No. 1, Livingston, Montana* (1894).

[25] Eugene Stebinger, "The Montana Group of Northwestern Montana," *U. S. Geol. Survey Prof. Paper 90* (1914), p. 62.

stone of eastern Colorado, which the writer regards as an eastern remnant of the Frontier formation, is entirely below the Fort Hays[26] limestone of Niobrara[5] age, but much of the Frontier formation in western Wyoming contains Niobrara fossils.

The writer believes that the best way to divide the shale will be to use the two major groups, Colorado[27] and Montana,[28] that are now in the literature of Montana and Utah, but which were first used in eastern Colorado. The dividing line between the two groups is the top of the Niobrara faunal zone, which is a mappable horizon throughout a large area in the plains states, but which has been mapped very little in western Wyoming and Montana. However, the men most familiar with the Niobrara claim that they are mapping its top farther and farther west. If it is possible to include all the Upper Cretaceous marine shale in the two groups, it may prove more acceptable to call the upper group Pierre[5] instead of Montana, since Pierre was first introduced and is used more generally. Such a classification would call the shale between the Dakota and the Frontier the Lower Colorado; the shale between the Frontier and the top of the Niobrara faunal zone the Upper Colorado; the shale between the top of the Niobrara and the base of the Eagle the Lower Pierre or Lower Montana; the shale between the Eagle and the Mesaverde the Middle Pierre or Middle Montana; and the shale between the Mesaverde and the Foxhills the Upper Pierre or the Upper Montana. This classification does not provide for the areas where the top of the Niobrara is not now mapped or may never be mapped. In western Colorado the Mancos[29] shale includes all strata from the Dakota up to the base of the Mesaverde and would not fit well into this system, but several geologists working in that district believe that the Mancos can be divided into the units of other areas, and that the name Mancos might be eliminated. In western Wyoming it may be best to use one name for the shale between the Frontier and the Eagle where the top of the Niobrara has not been mapped, at least until it has been mapped, but such a name could be followed by a bracket to show that it was Upper Colorado-Lower Pierre.

[26] B. F. Mudge, "Notes on the Tertiary and Cretaceous Periods of Kansas," *U. S. Geol. and Geog. Survey Terr.*, Vol. 2 (1876), pp. 218–21.
S. W. Williston, "The Niobrara Cretaceous of Kansas," *Kansas Acad. Sci. Trans. for 1891–1892*, Vol. 13 (1893), pp. 108–09.

[27] C. A. White, "Report on the Paleontological Field Work for the Season of 1877," *11th Ann. Rept. U. S. Geol. & Geog. Survey Terr. for 1877*, pp. 179, 186–87.

[28] G. H. Eldridge, "On some Stratigraphical and Structural Features of the Country about Denver, Colorado," *Colorado Sci. Proc.*, Vol. 3 (1888).

[29] Whitman Cross, *U. S. Geol. Survey Geol. Atlas No. 57*, Telluride, Colo. (1899), p. 4.

In the eastern plains there are two limestones, the Greenhorn[30] and Niobrara-Timpas[30]-Fort Hays, which have been mapped over wide areas and are valuable stratigraphic horizons. They should continue as formations or members of the groups suggested, but one name, probably the Fort Hays, should supersede the names Timpas and Niobrara. There is also an important siliceous shale member, the Mowry[31] or Aspen,[32] which extends from western Wyoming to the Black Hills of South Dakota but whose exact north and south limits are unknown. It should, of course, stay in the literature as a siliceous shale member, but the name Aspen could well be dropped.

In conclusion, the groupings and changes suggested may not be the best ones and may prove unacceptable, but the writer repeats that the present nomenclature of the Upper Cretaceous is very confusing and should be revised and simplified. He believes that the committee on geologic names could well encourage conferences of federal, state, university, and economic geologists to consider such situations, and to attempt to simplify geologic names. The writer hopes that this paper on the Upper Cretaceous will arouse such discussion, lead to more research on the problem, and perhaps to a conference of those most interested and familiar with it. He thinks that any new groupings or changes should have the approval of most of the geologists in the particular area and asks that none of the suggestions made in this paper be used unless they are approved by the majority of the other geologists. To attempt to force a different grouping that was not generally acceptable would only make the literature more confusing.

DISCUSSION

Charles S. Lavington, Denver, Colorado (discussion received May 19, 1937): Mr. Bartram assumes that the source of all the Upper Cretaceous sediments of the Rocky Mountain region was far on the west in Utah, Idaho, and British Columbia. On the contrary, I believe that there is ample evidence that it did not all come from the west. For example in eastern Colorado some of the members of the Dakota, and the so-called "Greasewood" sandstone appear to thin out toward the west and the Codell sandstone of western Kansas also appears to thin and pinch out in places on the west in eastern Colorado. Furthermore, there are sandstones in the Pierre in western Nebraska which do not appear to connect with the sandstones of the Pierre farther west. There is also some evidence that the Hygiene series of northeastern

[30] G. K. Gilbert, "The Underground Water of the Arkansas Valley in Colorado," *U. S. Geol. Survey 17th Ann. Rept.*, Pt. II (1896), pp. 565–67.

[31] N. H. Darton, "Geology and Underground Water Resources of the Central Great Plains," *U. S. Geol. Survey Prof. Paper 32* (1905), p. 187.

[32] A. C. Veatch, "Geography and Geology of a Portion of Southwestern Wyoming." *U. S. Geol. Survey Prof. Paper 56* (1907), pp. 64–65.

Colorado and the Mesaverde of west-central Colorado had a local source somewhere in the vicinity of central Colorado. The Upper Cretaceous beds are more than 9,000 feet in thickness in the vicinity of New Castle, Colorado, and probably still thicker in the vicinity of Craig. In the Denver basin also there are more than 8,000 feet of Upper Cretaceous strata, and these greater thicknesses occur where the sandstones thicken.

The present group boundaries, as defined in eastern Colorado, are easily recognizable, represent lithologic changes, and there should be no need to move them. The top of the Niobrara formation, which represents the division between the Colorado and Montana groups, is the first readily recognizable marker in well cuttings in northeastern New Mexico, eastern Utah, Colorado, western Kansas, western Nebraska, southwestern South Dakota, and eastern Wyoming, and is also easily placed in the field.

The name Mancos, which includes Benton, Niobrara, and part of the Pierre or Montana, can well be discarded.

John G. Bartram (discussion received, June 1, 1937): Mr. Lavington states there is ample evidence that all the Upper Cretaceous sediments did not come from the west. I admit that a little may have come from other directions, but very little, and I do not believe he has proved his point. The westward thinning of a member of the Dakota group and of the thin Codell sandstone would not alone disprove a western source for their sands. There could be local or fairly large areas in which they were not deposited or from which they were eroded. I can not agree with his suggestion that the Hygiene and Mesaverde formations might have had a local source in central Colorado. I do not know of any conglomerates or coarser sediments in the Pierre or Montana rocks of central Colorado, such as one would expect around a land mass large enough to furnish the formations in question. I believe that the far western land mass and the geosyncline along its eastern side moved eastward and that in Mesaverde time the bottom of the trough was near New Castle and Craig, Colorado, and that the Mesaverde sediments were thickest there in the bottom of the geosyncline, but that they came from a western source.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 21, NO. 7 (JULY, 1937), PP. 914-946, 1 FIG.

EVOLUTION OF GULF COAST CRUDE OIL[1]

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ABSTRACT

Comparison of the A.P.I. gravity and percentage content respectively of Miocene, Oligocene, and Eocene Gulf Coast crude oils from depths of 3,000 to 5,000 feet with the oils of corresponding age from depths of 5,000 to 7,000 feet shows that the A.P.I. gravity of the fractions and the percentage content of the lower boiling fractions tend to increase with depth and age. The base of both the lower and the higher boiling fractions tends to change with increasing depth and age from naphthenic to intermediate, and almost to paraffinic. In order of similarity, those age-depth groups of crude oils are arranged: shallower Miocene, shallower Oligocene, deeper Miocene, shallower Eocene, deeper Oligocene, deeper Eocene.

That variation of the Gulf Coast crude is consistent with transformation under the influence of time and some factor or factors proportional to depth below the surface but is inconsistent with alteration under the influence of time and some factor or factors proportional to nearness to the surface. The theory of evolution of the Gulf Coast crude oils from heavy naphthenic ancestral oils under the influence of time and some depth factor or factors therefore still is advocated. The evolution consists in, (a) decrease of the specific gravity of all but the lowest boiling fractions, (b) increase in percentage content of the lower boiling fractions, and (c) transformation of the base from naphthenic toward and almost to paraffinic. Cracking can not be the main reaction in the evolution. Methanation, possibly plus cracking, is regarded as the most plausible explanation of the evolution.

This law of the variation of crude oil is only one of many; and occurrences of one type do not preclude the existence of other types.

INTRODUCTION

This paper presents the results of a more exhaustive study than that which was reported in "Natural History of the Gulf Coast Crude Oil."[3] The percentages of gasoline, kerosene, gas oil, lubricating fractions, and residuum were used in that study as the criteria characterizing the composition of the crude oil. Those criteria, however, are rather inexact and arbitrary for that purpose. The absence of kerosene in the Miocene crude oils, for example, is the result of the definition of kerosene as having a certain range of boiling point and a certain maximum specific gravity. In the Miocene Gulf Coast crude oil, the fractions which distill over within the specific range have specific gravities exceeding that maximum and therefore are classed as gas oil. An extra light oil, furthermore, may be light be-

[1] Manuscript received, April 14, 1937. Read before the Association at Los Angeles, March 19, 1937.

[2] Humble Oil and Refining Company.

[3] Donald C. Barton, "Natural History of the Gulf Coast Crude Oil," *Problems of Petroleum Geology*, Amer. Assoc. Petrol. Geol. (1934), pp. 109–55.

cause of its extra content of light constituents, or because of the low specific gravity of its constituent fractions, or because of both. The composition of crude oil stated in terms of the percentage content of gasoline, kerosene, gas oil, lubricating fractions, and residuum gives only approximate indication of the variation in the character of the individual fractions among different crude oils. In the Hempel method, which the United States Bureau of Mines uses in making its analyses of crude oil, the cuts are taken at 50 degrees Centigrade and every 25 degrees from 50 degrees to 275 degrees at atmospheric pressure; at 200 degrees at 40 millimeters of mercury vacuum; and at every 25 degrees from 200 degrees to 300 degrees at 40 millimeters pressure. The specific gravity of a cut is directly related to its molecular composition, and as the cuts are fairly narrow, it is an approximate empirical criterion of the molecular character of a cut. State-

TABLE I

MEAN PERCENTAGE COMPOSITION OF GULF COAST CRUDE OILS BY 25 DEGREES CENTIGRADE DISTILLATION FRACTIONS

	3,000–5,000-Foot Zone					*5,000–7,000-Foot Zone*		
Distillation Range *Atmospheric Pressure* *(Degrees Centigrade)*	*Miocene*	*Miocene with Weighted Spindletop*	*Miocene (Two very Divergent Analyses Omitted)*	*Oligocene**	*Eocene*	*Miocene*	*Oligocene**	*Eocene*
50– 75	—	—	—	—	—	—	0.5	0.6
75–100	0.5	0.5	0.2	0.6	1.9	0.3	3.2	5.2
100–125	1.1	1.1	0.7	1.0	4.4	0.4	4.2	7.7
125–150	3.3	2.0	0.8	1.0	4.3	0.8	4.4	6.7
150–175	3.4	1.7	1.1	3.9	4.5	2.4	5.0	6.5
175–200	3.8	3.2		3.6	5.0	3.6	5.5	5.9
200–225	5.2	5.3		6.2	5.8	5.9	6.5	6.5
225–250	8.0	7.9		9.0	8.1	9.1	9.6	8.7
250–275	11.6	11.5		13.4	10.4	13.0	11.0	10.9
40 mm. Pressure (Degrees Centigrade)								
0–200	8.2	8.0		8.5	7.3	9.0	6.7	7.8
200–225	9.2	9.6		9.6	7.2	9.3	7.6	7.7
225–250	7.6	7.9		7.6	6.8	8.3	6.2	6.1
250–275	6.8	7.3		7.0	6.2	6.6	5.5	4.8
275–300	7.9	8.3		7.7	6.8	7.9	6.4	5.0
Residuum	23.1	25.8	25.5	20.9	21.0	23.5	18.0	9.6
"Carbon"	1.3	1.3		1.1	1.7	1.7	0.6	0.6
Sulphur	0.25	0.36		0.31	0.19	0.25	0.12	0.12

* In the main, th so-called "Middle Oligocene," which by many stratigraphers is now being referred to the basal Miocene.

TABLE II

A.P.I. GRAVITY OF THE 25 DEGREES CENTIGRADE DISTILLATION FRACTIONS

	3,000–5,000-Foot Zone					5,000–7,000-Foot Zone		
Distillation Range *Atmospheric Pressure* *(Degrees Centigrade)*	*Miocene with Weighted Spindletop*	*Miocene*	*Miocene (Two very Divergent Analyses Omitted)*	*Oligocene*	*Eocene*	*Miocene*	*Oligocene*	*Eocene*
50– 75	72.7	75.1	70.4				78.4	74.0
75–100	65.9	65.8	64.0	59.9	64.2	66.4	63.8	65.4
100–125	59.2	57.7	58.9	56.2	56.5	60.2	57.0	55.6
125–150	53.2	52.0	52.8	52.0	51.4	54.2	52.3	50.5
150–175	47.7	45.9		45.4	47.3	45.6	48.0	47.6
175–200	41.3	40.2		39.7	42.8	41.4	44.1	45.7
200–225	36.2	35.9		36.0	39.5	37.0	40.4	43.1
225–250	32.6	32.8		32.7	35.8	34.0	36.8	39.8
250–275	29.9	30.1		30.2	32.9	31.2	34.6	36.5
40 mm. Pressure (Degrees Centigrade)								
0–200	26.5	27.9		27.0	30.2	28.2	30.3	33.8
200–225	25.2	25.9		26.2	29.4	27.3	29.5	33.5
225–250	23.5	24.4		24.3	27.8	25.5	27.6	32.0
250–275	21.02	22.4		22.8	26.0	23.7	25.6	30.5
275–300	20.1	20.8		21.1	24.0	22.0	23.7	28.9
Residuum	16.9	17.1		17.3	17.4	17.1	19.1	19.2

ment of the composition of a crude oil in terms of the percentage and gravity of these cuts gives a much more detailed and refined characterization than the summarized statement of the composition in terms of gasoline, kerosene, etc. But with the use of the latter, less exact characterization of the composition of crude oil, the earlier study definitely showed a systematic increase of the lighter constituents and necessarily a corresponding decrease of the heavier constituents with increasing depth and age of the crude oil. The present study is a more exact investigation of the character of that variation.

Summarized basic data for the variation of Gulf Coast crude oil are given in Tables I and II. These data are based on U. S. Bureau of Mines analyses of Gulf Coast crude oils. The number of analyses from which these data were compiled are given in Table III. In order greatly to reduce the tediousness of handling the data, the crude oils were divided into two groups: (1) those coming from producing horizons at depths between 3,000 and 5,000 feet; and (2) those coming from producing horizons at depths between 5,000 and 7,000 feet. The

TABLE III

NUMBER OF ANALYSES AND THE MEAN DEPTH OF PRODUCING SANDS FROM WHICH THE CRUDE OIL CAME

Distillation Range	*3,000–5,000-Foot Zone*			*5,000–7,000-Foot Zone*		
Atmospheric Pressure (Degrees Centigrade)	*Miocene*	*Oligocene*	*Eocene*	*Miocene*	*Oligocene*	*Eocene*
50– 75	1				2	1
75–100	6	3	6		6	3
100–125	10	3	8	1	6	3
125–150	11	4	8	4	6	3
150–175	18	7	8	4	7	3
175–200	29	9	11	5	8	3
200–225	27	9	11	5	8	3
225–250	27	9	11	5	8	3
250–275	27	9	11	5	8	3
40 mm. Pressure (Degrees Centigrade)						
0–200	27	9	11	5	8	3
200–225	27	9	11	5	8	3
225–250	27	9	11	5	8	3
250–275	27	9	11	5	8	3
275–300	27	9	11	5	8	3
Residuum	16	7	9	5	7	3
Carbon	35	9	11	5	8	3
Sulphur	35	9	11	5	8	3
Mean Depth	3,549	3,804	3,530	5,640	6,143	5,193

study of the variation of the crude oil with depth was based on the variation between the respective means for the upper zone and the corresponding means for the lower zone.

DESCRIPTIVE DATA

VARIATION OF PERCENTAGE CONTENT OF FRACTIONS WITH DEPTH AND AGE

The content of the lower boiling fractions in the oils of each of the ages is greater in the 5,000–7,000-foot zone than in the oils of the 3,000–5,000-foot zone; and within each of those depth zones the content of those lower boiling fractions increases with increasing age of the producing horizons from which the samples of crude oil were taken. Conversely, the content of the higher boiling fractions is lower in the deeper groups of crude in comparison with the shallower groups of corresponding age and is lower in the older oils in each of the two depth groups of crude oils. The fact of those two laws of variation of the crude oil can be seen in the summary given in Table IV. The data of Tables I, II, and IV are the same as those which were used in "Natural History of the Gulf Coast Crude Oil,"[3] and

these two laws of variation of the crude are essentially the same two laws which are found in that earlier study. The slight difference holds that the two laws just stated refer solely to percentage content of fractions boiling within certain temperatures and pressure ranges, whereas the similar laws of that earlier study refer to percentage content of fractions which in the main depend upon the boiling range but which also depend in part upon the gravity of the fractions.

Statistically, the study is based on fewer analyses than the writer would like; only three analyses were available for Eocene crude oils from depths between 5,000 and 7,000 feet and only five analyses for Miocene oils from that zone, but the pattern of variation is consistent throughout Table IV, and the differences are large, except in case of the Miocene crude oil from depths of 3,000–5,000 feet.

TABLE IV

VARIATION OF THE PERCENTAGE CONTENT OF LOW, MEDIUM, AND HIGH BOILING FRACTIONS WITH DEPTH AND WITH AGE

I. A. Fractions Boiling between 0 Degrees and 275 Degrees Centigrade at Atmospheric Pressure			
	Miocene	*Oligocene*	*Eocene*
3,000–5,000 foot zone	33.0 (31.3)*	37.8	44.6
5,000–7,000 foot zone	34.4	49.5	58.6
B. Fractions Boiling between 0 Degrees and 300 Degrees Centigrade at 40 mm. Pressure (Lubricating Fractions)			
3,000–5,000-foot zone	41.1 (41.8)*	40.9	34.3
5,000–7,000-foot zone	41.6	32.1	31.5
C. Residuum. Fractions Which Do Not Boil Over below 300.1 Degrees Centigrade at 40 mm. Pressure			
3,000–5,000-foot zone	25.7 (26.8)*	21.3	21.1
5,000–7,000-foot zone	23.9	18.3	9.6
II. Variation with Depth			
(Percentage 5,000–7,000-foot zone) less (percentage 3,000–5,000-foot zone)			
Fraction Boiling between	*0–275 Degrees Centigrade Atmos. P.*	*0–300 Degrees Centigrade 40 mm. P.*	*Residuum*
Miocene	+ 1.4	+0.5	− 1.9
Oligocene	+11.7	−8.8	− 3.0
Eocene	+14.0	−2.8	−11.5
III. Variation with Age (Increase with Age +)			
3,000–5,000 Feet			
Miocene to Oligocene	+ 4.8	−0.2	− 4.4
Oligocene to Eocene	+ 6.8	−6.6	− 0.2
5,000–7,000 Feet			
Miocene to Oligocene	+14.1	−9.5	− 5.6
Oligocene to Eocene	+ 9.1	−0.6	− 8.7

* Two very divergent analyses eliminated.

The two laws of variation which the table shows seem, therefore, to be real and not merely apparent. In conformity with the two

laws, the youngest group of oils, in which the depth factor has been working for the shortest time, shows the least variation with depth, and the oldest group of oil shows the greatest variation with depth; and the shallower group of oils, on which a weaker depth factor would have been working, shows less variation with age than the oils of the deeper group, on which a stronger depth factor would have been working.

VARIATION OF A.P.I. GRAVITY OF FRACTIONS WITH DEPTH AND AGE

The A.P.I. gravity of the individual distillation fractions tends to increase (specific gravity to decrease) with depth for all of the cuts of the crude oils of each of the three geologic ages, if the crude oils from the 3,000–5,000-foot zone are compared with those from the 5,000–7,000-foot zone. The size of the increase for each of the three geologic ages is shown in Table V. Three exceptions to the general rule are present; decrease of the A.P.I. gravity is shown by one of the cuts of the Miocene oils, and by two of the cuts of the Eocene oils. The three cases of decrease of the A.P.I. gravity (increase of the specific gravity) are all in cuts which distill over below 175°C. Those fractions of low boiling point show more irregularity in these studies than do those of higher boiling point. Different groups of oils, furthermore, seem to exist in some cases among oils of a common geologic period and seem probably to have original differences between the A.P.I. gravity of corresponding distillation cuts. In the case of the aberrant Miocene cut only four analyses were available for crude oils from the depth of 5,000–7,000 feet; and in the case of the two aberrant Eocene cuts only three analyses were available of crude oils from depths of 5,000–7,000 feet. Those three exceptions therefore easily might be the effect of such original differences in character. But the strong predominance of the increase of A.P.I. gravity with depth seems, therefore, to indicate a definite tendency for increase of A.P.I. gravity with depth in all of the distillation cuts.

The A.P.I. gravity of the bulk of the fractions of the crude oil tends to increase (specific gravity to decrease) with age; and the base of the crude oils tends to change from naphthenic toward paraffinic with age; but a strong suggestion is given of decrease of the A.P.I. gravity of the low boiling (light) fractions with geologic age (Table VI). All of the fractions distilling over below 225 degrees Centigrade at atmospheric pressure are lighter and have a higher A.P.I. (lower specific) gravity in the 3,000–5,000-foot Miocene crude oils than in the Oligocene oils of the same depth zone; and for most of the fractions the differences are substantial. And similarly in the

TABLE V

INCREASE OF A.P.I. GRAVITY WITH DEPTH IN THE 25 DEGREES CENTIGRADE DISTILLATION FRACTIONS

I. *Distillation Fraction*	*75 to 100*	*100 to 125*	*125 to 150*	*150 to 175*	*175 to 200*	*200 to 225*	*225 to 250*	*250 to 275*	*0 to 200*	*200 to 225*	*225 to 250*	*250 to 275*	*275 to 300*	*Residuum*
	At Atmospheric Pressure								*At 40 Millimeters Pressure*					
	(Mean A.P.I. Gravity 5,000–7,000 Feet) less (Mean A.P.I. Gravity 3,000–5,000 Feet)													
Miocene	+0.5	+1.0	+1.0	−2.1	+0.1	+0.8	+1.4	+1.3	+1.7	+2.1	+2.0	+2.7	+1.9	+0.2
Oligocene	+3.9	+0.8	+0.3	+2.6	+4.4	+4.4	+4.1	+4.4	+3.3	+3.3	+3.3	+2.8	+2.6	+1.8
Eocene	+1.2	−0.9	−0.9	+0.3	+2.9	+3.6	+4.0	+3.6	+3.6	+4.1	+4.2	+4.5	+4.8	+1.8
II. *Means*														
Miocene		+0.1				+0.9					+ 2.1			+0.2
Oligocene		+1.9				+4.3					+ 3.1			+1.8
Eocene		−0.1				+3.5					+ 4.2			+1.8
III. *Means Times Percentage Content of Those Fractions*														
Miocene		+0.1				+ 0.3					+ 0.9			+0.1
Oligocene		+2.1				+14.2					+11.2			+3.4
Eocene		−0.2				+10.5					+13.4			+2.6

TABLE VI

INCREASE OF A.P.I. GRAVITY WITH GEOLOGIC AGE IN THE 25 DEGREES CENTIGRADE DISTILLATION FRACTIONS

I. Distillation Fraction (Degrees Centigrade)	*75 to 100*	*100 to 125*	*125 to 150*	*150 to 175*	*175 to 200*	*200 to 225*	*225 to 250*	*250 to 275*	*0 to 200*	*200 to 225*	*225 to 250*	*250 to 275*	*275 to 300*	*Residuum*
	At Atmospheric Pressure								*At 40 Millimeters Pressure*					
A. 3,000–5,000 Feet														
Miocene to Oligocene	−6.0	−3.0	−1.2	−2.3	−1.6	−0.2	+0.1	+0.3	+0.5	+1.0	+0.8	+1.8	+1.0	+0.4
Oligocene to Eocene	+4.3	+0.3	−0.6	+1.9	+3.1	+3.5	+2.8	+2.7	+3.2	+3.2	+3.5	+3.2	+2.9	+0.1
B. 5,000–7,000 Feet														
Miocene to Oligocene	−2.6	−3.2	−1.9	+2.4	+2.7	+3.4	+2.8	+3.4	+2.1	+2.2	+2.1	+1.9	+1.7	+2.0
Oligocene to Eocene	+1.6	−1.4	−1.7	−0.4	+1.6	+2.9	+3.0	+1.9	+3.5	+4.0	+4.4	+4.9	+5.2	+0.1
II. Means														
A. 3,000–5,000 Feet														
Miocene to Oligocene		−3.1				−0.3					+1.0			+0.4
Oligocene to Eocene		+1.5				+3.0					+3.2			+0.1
B. 5,000–7,000 Feet														
Miocene to Oligocene		−1.3				+3.1					+2.0			+2.0
Oligocene to Eocene		−0.4				+2.3					+4.4			+0.1
III. Means Times Percentage Content of Those Fractions														
A. 3,000–5,000 Feet														
Miocene to Oligocene		−0.18				−0.1					+4.0			+0.9
Oligocene to Eocene		+0.11				+0.9					+11.5			+0.0
B. 5,000–7,000 Feet														
Miocene to Oligocene		−0.13				+9.6					+ 7.2			+4.0
Oligocene to Eocene		−0.08				+7.1					+13.6			+0.1

crude oils from the deeper 5,000–7,000-foot zone, the fractions boiling below 175 degrees Centigrade atmospheric pressure are lighter in the Miocene crude oils than in the Oligocene crude oils. Over the age period Oligocene to Eocene, one light fraction, that distilling over between 125 and 150 degrees Centigrade at atmospheric pressure, is lighter in the 3,000–5,000-foot Oligocene oils than in the Eocene oils from that depth zone; and in the oils from the 5,000–7,000-foot zone, the three fractions distilling over between 100 and 175 degrees Centigrade at atmospheric pressure are lighter in the Oligocene oils than in the Eocene oils. All other fractions show a decrease in the A.P.I. (an increase in the specific) gravity with age, and in general the increase is substantial; for a large number of the fractions, the decrease ranges from 2 to 4½ degrees A.P.I. The decrease (increase of the specific gravity) for the residuum is too small to be significant statistically in three of the four cases; nevertheless, all four cases show a decrease in the A.P.I. gravity of the residuum. Original genetic differences in character between the Miocene, Oligocene, and Eocene crude oils may account for part of the observed differences in those lighter fractions. Nevertheless, the occurrence of the decrease in A.P.I. (increase of specific) gravity in some of the very light fractions in each of the four groups of oils of Table VI and the consistent and, in the main, substantial reverse relation in the higher boiling fractions, suggests strongly a tendency toward the reverse variation with age in the low boiling fractions. But quantitatively the percentage content of the fractions which are affected by this reverse relation of decrease of A.P.I. (increase of specific) gravity with age is small compared to that of the rest of the fractions in which substantial increase of A.P.I. (decrease of specific) gravity takes place with age. And the total influence on the oil is overwhelmingly a very substantial increase in the A.P.I. (decrease of the specific) gravity of the crude oil as a whole.

CHANGE OF BASE OF CRUDE WITH DEPTH

Change of the base from naphthenic toward, and almost to, paraffinic with increasing depth is definitely shown by the Miocene, Oligocene, Jackson Eocene, and Lower Eocene crude oils; and a similar change with increasing age is indicated as probable.

As empirical indicators of the base of a crude oil, the United States Bureau of Mines uses the gravity of two fractions which distill over respectively between 250 and 275 degrees Centigrade at atmospheric pressure and between 275 and 300 degrees Centigrade at 40 millimeters of mercury pressure.[4]

[4] E. C. Lane and E. L. Garton, "'Base' of a Crude Oil," *U. S. Bureau of Mines, Report Investigations 3279* (September, 1935), 12 pp.

The following empirical relations have been found by the United States Bureau of Mines: (a) that the lower boiling fractions are (1) paraffinic, if the specific gravity of the first of those two fractions (key fraction No. 1) is 0.825 or less (40 degrees A.P.I. or higher), (2) intermediate, if the specific gravity of the fraction is between 0.825 and 0.860 (between 40 degrees and 33 degrees A.P.I.), and naphthenic, if the specific gravity of that fraction is 0.860 or higher (33 degrees A.P.I. or less); and (b) that the higher boiling fractions are: paraffinic if the specific gravity of the other key fraction (No. 2) is 0.877 or less (30 degrees A.P.I. or more); intermediate if the specific gravity of that fraction is between 0.877 and 0.930 (between 30 degrees and 20 degrees A.P.I.), and naphthenic if specific gravity of that fraction is c.930 or more (20 degrees A.P.I. or less).

Graphs of specific gravity plotted against depth for each of the two key fractions are given in Figure 1.

Decreasing specific gravity with increasing depth is shown definitely in both of the two key fractions by the Miocene, Oligocene, Jackson Eocene and Lower Eocene crude oils. The product correlation coefficients[5] and the probability factor[6] are given in Table VII, *I*. Significant correlation is shown by the Miocene and Oligocene crude oils for both key fractions, and by the Eocene crude oils for key fraction No. 2. The Lower Eocene crude oils taken by themselves show a fairly significant degree of correlation in both key fractions. The correlation for the Jackson Eocene crude oils has a lower degree of probability, 91 chances out of 100; but it conforms to the correlation shown by the Miocene, Oligocene, and Lower Eocene crude oils and therefore presumably is significant. A low degree of correlation is shown by both key fractions of the Pliocene crude oils, but has no great degree of significance. In both key fractions of the Pliocene crude oils, however, the correlation is in the direction of decrease of specific gravity with depth.

Change in the character of the base from naphthenic at shallow depth to intermediate at moderate depth and to paraffinic at very great depth is definitely indicated for the oils of Miocene, Oligocene, and Eocene age. The higher boiling fractions have progressed farther in the transformation from naphthenic to paraffinic than have the lower boiling fractions. And expectably the higher boiling (heavier) fractions should become paraffinic at a shallower depth than should the lower boiling (lighter) fractions. The higher boiling fractions of

[5] R. E. Chaddock, *Principles and Methods of Statistics*, Houghton Mifflin and Co. (1925), p. 268.

[6] R. A. Fisher, *Statistical Methods for Research Workers*, Oliver and Boyd (London, 1930), p. 176.

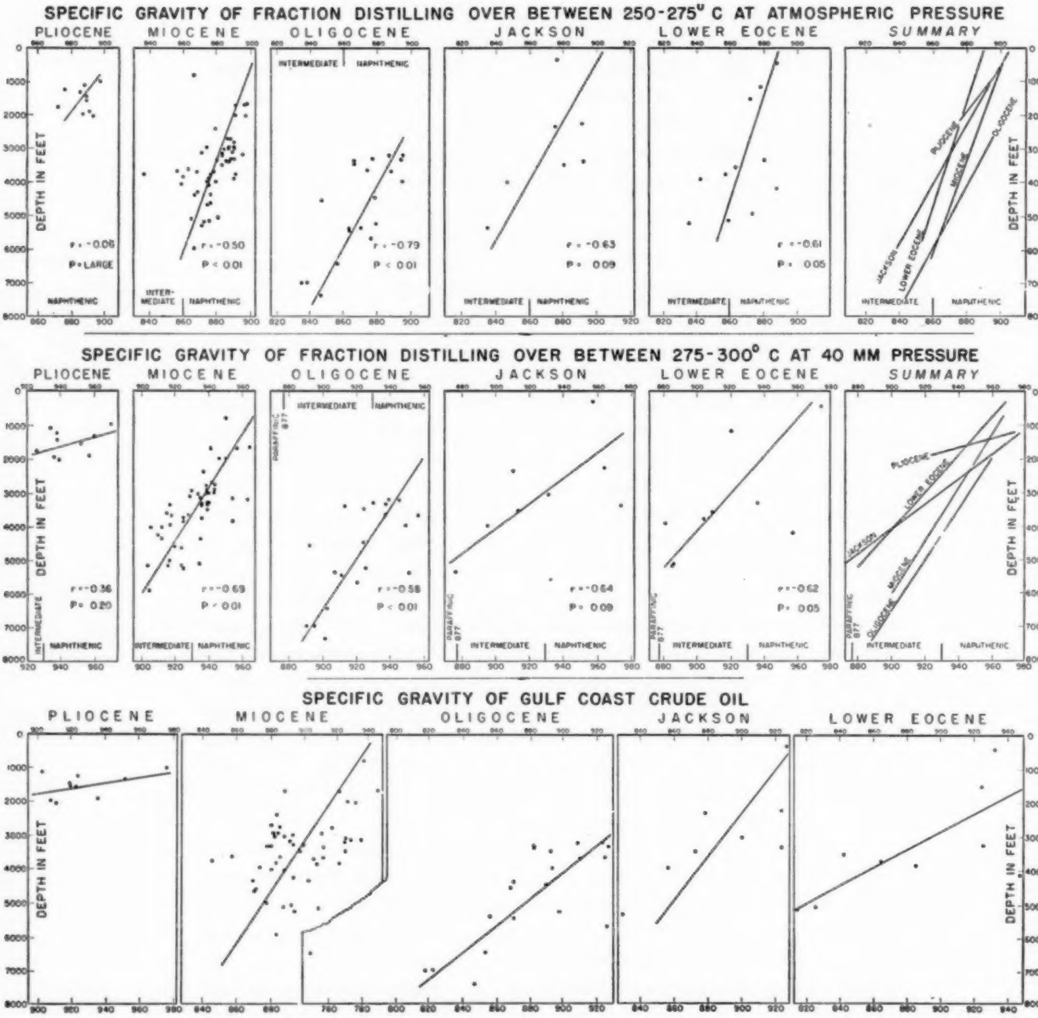

FIG. 1.—Depth variation of the specific gravity of key fraction No. 1, key fraction No. 2, and of the crude oil respectively for Pliocene, Miocene, Oligocene, Jackson Eocene, and Lower Eocene crude oils of the Gulf Coast. Data from the analyses by the United States Bureau of Mines.

the Eocene crude oil tend to be naphthenic at depths less than 2,500–3,000 feet. Whereas, the base of the lower boiling fractions tends to be naphthenic down to depths of 4,500 to 5,000 feet; and in the Miocene and Oligocene crude oils, the dividing line between naphthenic at shallower depth, and intermediate at greater depth tends to be at a depth of 3,500–4,000 for the higher boiling fractions and at a depth of 6,000 feet in the lower boiling fractions (Table VII, *II*);

TABLE VII

DECREASE OF SPECIFIC GRAVITY WITH DEPTH

I. Correlation and Probability Factors, and Rate of Decrease

	Key Fraction No. 1 Distilling between 250 and 275 Degrees Centigrade Atmospheric Pressure			*Key Fraction No. 2 Distilling between 275 and 300 Degrees Centigrade 40 mm. Pressure*		
	Correlation Coefficient r*	*Probability† Factor P*	*Specific Gravity Decrease per 1000 Feet*	*Correlation* Coefficient r*	*Probability† Factor P*	*Specific Gravity Decrease per 1000 Feet*
Pliocene	−0.06	large		−0.36	0.20	
Miocene	−0.50	<0.01	0.008	−0.69	<0.01	0.014
Oligocene	−0.79	<0.01	0.012	−0.58	<0.01	0.014
Jackson Eocene	−0.63	0.09	0.011	−0.64	0.09	0.027
Lower Eocene	−0.61	0.05	0.010	−0.62	0.05	0.018
Eocene	−0.42	0.08	0.008	−0.64	0.01	0.010

II. Depth at Which the Base of the Mean Crude Should Become Intermediate and Paraffinic

	Key Fraction No. 1		*Key Fraction No 2*	
Become:	*Intermediate*	*Paraffinic*	*Intermediate*	*Paraffinic*
Pliocene	(5,000)‡		(3,000)‡	
Miocene	6,000	10,500 feet	3,500	8,000−
Oligocene	6,000	9,000 feet	4,000	8,000+
Jackson Eocene	5,000	8,000 feet	3,000	5,000−
Lower Eocene	4,500	9,500 feet	2,500	5,000+

* 1.00=perfect correlation.
† Probability factor shows chance that this observed correlation is accidental; 1.00=certainty.
‡ Extrapolation based on rate of variation of Miocene crude oils.

the dividing depth between naphthenic and intermediate base tends to be 1,500–2,000 feet shallower in the higher boiling fractions than in the lower boiling fractions of the same crude oils. The base of the higher boiling fractions of the Eocene and Oligocene crude oils is almost paraffinic; and in view of the definite and probably linear change in the character of the base, expectably the base of the crude oils should tend to become paraffinic below certain depths (Fig. 1). The Eocene crude oils should tend to be paraffinic at depths greater than 5,000 feet in the higher boiling fractions and 8,000–9,500 feet in the lower boiling fractions. The Miocene and Oligocene crude oils should tend to become paraffinic at depths greater than 8,000 feet

in the higher boiling (heavy) fractions and 9,000–10,500 feet in the lower boiling fractions.[7]

The general trend, and the complication in the trend, toward change in the character of the base from naphthenic toward paraffinic, with age, are shown by the summary diagram of the variations of the specific gravity of the two key fractions with depth (Fig. 1). The slope of the line of mean variation and the position of the center of mean depth and mean specific gravity for the oils of each age is only qualitatively significant, for statistically they depend upon too few observations and therefore are only approximately accurate.

The Miocene and Oligocene crude oils, on the whole, seem to be more naphthenic than the Eocene crude oils; and, on the whole, the Jackson Eocene crude oils are more naphthenic than the older Lower Eocene oils.

The mean values of both Pliocene key fractions in Figure 1 have a lower specific gravity (higher A.P.I. gravity) than that which the corresponding key fractions of the average Miocene or Oligocene crude would have at comparably shallow depths. That fact, in considerable part, however, may be more apparent then real, for two reasons: (1) that only a minority of the crude oils whose analyses were used are indubitably Pliocene; and (2) that the extrapolation of the mean specific gravity of the Miocene, Oligocene, and Eocene crude oils respectively, from mean depths of 3,500, 4,800, and 3,100 feet to a depth of 1,500 feet, is only approximate. Nevertheless, with allowance for those factors, the specific gravity of the two key fractions of average Pliocene crude oil seems to be at least as low (A.P.I. gravity as high) as that of the corresponding key fractions of the Miocene and Oligocene crude oils and, if anything, slightly lower.

Determination of the law or laws of change in the character of crude oil with increasing geologic age is more complicated than determination of the laws of variation with depth. In the comparison of oils of one geologic age but of different depths from a single petroleum province such as the Gulf Coast, indigenous oils of different original character may be present, but are likely to be found distributed irregularly at all depths. The mean original character of the shallow, medium depth, and deep oils, therefore, should have been approximately identical. In comparison of oils of different geologic age but of common depth, from a common petroleum province, the oils of different geologic age presumably will have had a different

[7] Paraffinic Miocene oil is being produced from 11,615–30 feet in the middle Miocene at Livette, Louisiana. The A.P.I. gravity of key fraction No. 1 is 40°; and of key fraction No. 2, 30°, according to a U. S. Bureau of Mines analysis.

original character; and the differences which are observed in that comparison will be the combination of the original differences between oils plus the effects of changes with age. Close similarity in the character of the ancestral oils of the Gulf Coast crude oils of the different ages was postulated in the report on "Natural History of the Gulf Coast Crude Oil." A subsequent study of wider scope and of greater refinement, still under way, has convinced the writer that considerable differences of character existed between the ancestral oils and that not all Gulf Coast oils of common age have had ancestral oils of common character.

An age effect which in the main consists in a decrease of the specific gravity of at least most of the fractions of the crude oil and in a transformation of the character of the oil from naphthenic toward paraffinic is suggested strongly by the data of Tables IV and VI, but in a confused way in Figure 1. But the change is not clearly a linear function, nor does it clearly affect all fractions of a crude similarly. A yet more refined study seems necessary definitely to formulate the law of variation of the character of crude oil with age.

TABLE VIII

VARIATION OF CONTENT OF "CARBON RESIDUE" AND OF SULPHUR WITH AGE AND DEPTH

	"Carbon Residue" Per Cent of Crude	*Sulphur Per Cent of Crude*
I. Variation with Depth: (Mean 5,000–7,000 Feet) Less (Mean 3,000–5,000 Feet)		
Miocene	+0.4	−0.13
Oligocene	−0.5	−0.19
Eocene	−1.0	−0.06
II. Variation with Age		
3,000–5,000 foot Zone		
Miocene to Oligocene	−0.2	−0.05
Oligocene to Eocene	+0.5	−0.13
5,000–7,000 foot Zone		
Miocene to Oligocene	−1.1	−0.11
Oligocene to Eocene	0	0

VARIATION OF CONTENT OF SULPHUR AND OF CARBON

The percent of sulphur in the Gulf Coast crude decreases slightly with age and depth (Table VIII) but the content of sulphur is low in Gulf Coast crude oils other than in exceptional crude oils such as the cap rock oil at Spindletop. The mean content of sulphur is highest in the Miocene crude oils from the 3,000–5,000-foot zone but is only 0.36 per cent. In both the Oligocene and Eocene mean crude oils from the 5,000–7,000-foot zones, it drops to the low value of 0.12 per cent.

The content of "carbon residue" does not show consistent varia-

TABLE IX

RELATIVE DEGREE OF SIMILARITY BETWEEN THE CRUDE OILS

	3,000–5,000-Foot Zone						5,000–7,000-Foot Zone					
	Miocene		*Oligocene*		*Eocene*		*Miocene*		*Oligocene*		*Eocene*	
*I. In Terms of Mean-Square Differences**												
3,000–5,000-Foot Zone	*A.P.I.*	*Per Cent†*	*A.P.I.*	*Per Cent*	*A.P.I.*	*Per Cent*	*A.P.I.*	*Per Cent*	*A.P.I.*	*Per Cent*	*A.P.I.*	*Per Cent*
Miocene	—	—	0.3	1.1	2.7	1.6	1.2	1.2	3.4	2.1	6.2	4.6
Oligocene	0.3	1.1	—	—	2.8	1.7	1.2	1.1	3.4	1.7	6.4	4.3
Eocene	2.7	1.6	2.8	1.7	—	—	2.0	2.3	0.9	1.0	3.4	3.3
5,000–7,000-Foot Zone												
Miocene	1.2	1.2	1.2	1.1	2.0	2.3	—	—	2.4	2.6	5.4	4.9
Oligocene	3.4	2.1	3.4	1.7	0.9	1.0	2.4	2.6	—	—	3.2	2.8
Eocene	6.2	4.6	6.4	4.3	3.4	3.3	5.4	4.9	3.2	2.8	—	—
II. Sequence of Similarity												
3,000–5,000-Foot Zone												
Miocene	x		1		3		2		4		5	
Oligocene	1		x		3		2		4		5	
Eocene	2		3–4		x		3–4		1		5	
5,000–7,000-Foot Zone												
Miocene	2		1		3		x		4		5	
Oligocene	4		2		1		3		x		5	
Eocene	5		4		2		3		1		x	

* $\sqrt{\frac{1}{n}\Sigma[(\text{A.P.I.})_a-(\text{A.P.I.})_b]}$ and $\sqrt{\frac{1}{n}\Sigma[(\text{per cent})_a-(\text{per cent})_b]}$.

† A.P.I. = A.P.I. gravity of a distillation fraction; per cent = the percentage content of that fraction; n = number of fractions used; a = any one of the mean analyses, and b of any other one of the mean analyses of the six depth-age groups, Tables I and II.

tion with either age or depth. The highest mean content of "carbon residue" is in the Miocene crude oils from the 5,000–7,000-foot zone, the next highest is in the Eocene crude oils from the 3,000–5,000-foot zone, and the least is in the Oligocene and Eocene crude oils from the 5,000–7,000-foot zone.

RELATIVE CLOSENESS OF SIMILARITY OF THE GROUPS OF CRUDE OILS

A law of closeness of similarity seems to hold according to which the sequence of similarity is: Miocene oils of the 3,000–5,000-foot zone, Oligocene oils of the 3,000–5,000-foot zone, Miocene oils of the 5,000–7,000-foot zone, Eocene oils of the 3,000–5,000-foot zone, Oligocene oils of the 5,000–7,000-foot zone, Eocene oils of the 5,000–7,000 -foot zone. According to this law, oils of one age from the shallower zone are most like the next younger oils of the deeper zone. The degree of similarity between the different groups of oils of Miocene, Oligocene, and Eocene age from the depth zones of 3,000–5,000 feet and 5,000–7,000 feet are shown in Tables VIII and IX.

The criterion which was used for the degree of relative similarity is the mean-square difference between the mean crude oils of the different groups. The difference was taken between the percentage content of a distillation fraction of the one crude and that of the corresponding fraction of the other crude. The sum of the squares of those differences for all the fractions was taken and divided by the number of fractions. The square root of the quotient is the mean-square difference between the two crude oils. A low mean-square difference indicates that two crude oils are closely alike; a large mean-square difference means that the crude oils were decidedly unlike. The mean-square differences were calculated in the same manner for the A.P.I. gravity of the distillation fractions. The mean-square differences which were obtained are tabulated in Table IX, Part *I*.

The sequence of similarity of each of the groups of the crude oils to all the other crude oils is given in Part *II* of that Table. The Miocene crude oil from the 3,000–5,000-foot depth zone for example is most like the Oligocene crude oil from the 3,000–5,000-foot zone and most unlike the Eocene crude oils from the 5,000–7,000-foot zone; and the order of increasing dissimilarity to the other three groups of crude oils is: Miocene crude oils of the shallower group, Eocene crude oils of the shallower group, and Oligocene crude oils of the deeper group.

The relative character of the mean crude oils of the different groups is expressed in Table X in terms of its mean-square difference from the mean Miocene crude oil of the 3,000–5,000-foot zone. In

Part *II* of Table X, the mean-square difference between that crude oil and the Eocene crude oil from the 5,000–7,000-foot zone is taken as 100 and the other differences are expressed in percentages of that difference. The law was stated in the writer's earlier paper, that the crude oils of different ages and depths had evolved from ancestral oils of a rather common type under the combined influence of a factor associated with depth and a factor associated with age; and that the present character of a crude oil tended to be merely a stage in that evolution, dependent on the age and depth of the crude oil. The figures of Table X, Part *III*, would represent the degree of evolution from the heavier type of oils in the Miocene of the 3,000–5,000-foot zone to the lighter type in the Eocene of the 5,000–7,000-foot zone.

TABLE X

CHARACTER OF THE CRUDE OILS IN TERMS OF DEVIATION FROM THE 3,000–5,000-FOOT MIOCENE CRULE OILS

*I. In Terms of Mean-Square Differences**						
	A.P.I. Gravity of a Fraction			*Percentage Content of a Fraction*		
Zone	*Miocene*	*Oligocene*	*Eocene*	*Miocene*	*Oligocene*	*Eocene*
3,000–5,000-foot	0	0.3	2.7	0	1.1	1.6
5,000–7,000-foot	1.2	3.4	6.2	1.2	2.1	4.6
II. In Terms of the Respective Difference between Mean-Square Differences for the 3,000–5,000-Foot Miocene and the 5,000–7,000-Foot Eocene Crude Oils Taken as 100						
Zone		*A*			*B*	
3,000–5,000-foot	0	5	46	0	23	34
5,000–7,000-foot	20	52	100	25	50	100

III. Means of II A and B			
Zone	*Miocene*	*Oligocene*	*Eocene*
3,000–5,000-foot	0	14	40
5,000–7,000-foot	22	51	100

* $\sqrt{\frac{1}{n}\Sigma[(\text{A.P.I.})_a - (\text{A.P.I.})_b]}$ and $\sqrt{\frac{1}{n}\Sigma[(\text{per cent})_a - (\text{per cent})_b]}$.

VARIATION INDEPENDENT OF DEPTH AND AGE

The correlated variations of certain characters of the crude oils independent of the variation with depth and age are shown in Table XI. In the preceding part of the paper, a variation in the character of the crude oil with depth and age has been shown to be present and to consist of (a) increase of the content of the lighter distillation fractions with depth, and (b) increase, in general, in A.P.I. gravity of the distillation fractions with depth. But most crude oils necessarily have a greater or less content of the respective fractions than the mean value for their respective depths and ages. In this section of the paper the problem is studied as to whether an increase of the content of the light fractions is accompanied by an increase or a decrease in

the A.P.I. gravity of those fractions and related questions in regard to correlation between the variations of other characters. The correlation was calculated between each pair of the following quantities: (a) percentage content of the light fractions, (b) A.P.I. gravity of the light fractions, (c) percentage content of residuum, (d) A.P.I. gravity of the residuum, (e) percentage content of carbon residue, (f) percentage content of sulphur. Calculation of the degree of correlation between the various quantities is tedious; and therefore, instead of calculating the correlation coefficients for all the distillation fractions, those which distill over between 200 and 250 degrees Centigrade at atmospheric pressure were used to represent the light fractions and the residuum was used to represent the heavy fractions. A correction factor for variation with depth was applied to reduce the A.P.I. gravity, percentage content of the fraction, and percentage content of sulphur to that which it theoretically should have at the mean depth of the 3,000–5,000-foot or 5,000–7,000-foot zone from which the crude oil came. These two narrowly restricted fractions now are regarded by the writer as not satisfactorily representing the oil as a whole, but it seems worth while to present the results for what they are worth.

The direct and universal correlations and lack of correlations which are indicated or suggested in Table XI are tabulated in Table XII. The weight of each correlation, good, fair, or possible, is indicated by the letter in parenthesis. A study based on a greater number of samples might show correlation between the variations of quantities between which no correlation is shown in this study, and might show no correlation between the variations of some of the quantities between which possible correlation is suggested; and it should be noticed that any pair of the three following suggested correlations is inconsistent with the existence of the third correlation: (1) percentage content of light fractions inversely with percentage content of residuum; (2) percentage content of the residuum inversely with the A.P.I. gravity of the residuum; and (3) percentage content of the light fractions inversely with the A.P.I. gravity of the residuum. That study might show also that certain correlated variations are characteristic of the shallow oils but not of the deeper oils, or of the younger oils but not of the older, or of the younger shallower oils but not of the older.

THEORETICAL CONNOTATIONS

GENERAL THESIS

The data of this study give trenchant evidence against three common theories in so far as they apply to the origin of Gulf Coast

TABLE XI

CORRELATION OF DEVIATION OF A.P.I. GRAVITY AND PERCENTAGE CONTENT FOR LIGHT FRACTIONS (200–250 DEGREES CENTIGRADE ATMOS.) AND FOR RESIDUUM, AND OF PERCENTAGE CONTENT OF CARBON RESIDUE AND OF SULPHUR, FROM THE VALUES NORMAL FOR THE DEPTH AND GEOLOGIC AGE OF THE CRUDE OIL

Geologic Age	*Miocene*						*Oligocene*				*Eocene*				*All Three Ages Both Depth Zones*	
Depth Zone in Feet	*3,000–5,000*				*5,000–7,000*		*3,000–5,000*		*5,000–7,000*		*3,000–5,000*		*5,000–7,000*			
Pearson Product Correlation Coefficient, r§ and Probability Factor, P†§*	*Ex. Spindletop* r	P	*Spindletop* r	P	r	P	r	P	r	P	r	P	r	P	r	P
I. All Values																
Per cent light fractions‡																
VS A.P.I. of light fractions‡	+.29	.30	−.48	.18	−.06	.90	−.78	.04	−.27	.60	+.39	.30	−.58	POOR; ONLY 3 ANALYSES	+.08	.55
VS Per cent of residuum	−.78	.01	+.39	.25	−.92	<.01	−.82	.03	−.39	.30	−.97	<.01	−.85		−.81	<.01
VS A.P.I. of residuum	+.46	.09	−.18	.60	+.43	.35	−.17	.70	−.91	<.01	−.84	<.01	−.20		−.32	.01
VS Per cent of carbon residue	−.57	.03	+.11	.70	−.80	.04	−.61	.15	−.04	.90	−.89	<.01	−.74		−.21	.11
VS Per cent of sulphur	−.23	.40	+.60	.06	−.88	.01	−.63	.15	−.03	.90	−.33	.40	−.60		−.40	<.01
A.P.I. light fractions																
VS Per cent of residuum	+.15	.60	−.79	.04	+.08	.90	+.38	.40	−.63	.15	−.40	.30	−.67		−.21	.11
VS A.P.I. of residuum	−.26	.40	+.78	<.01	+.04	.90	+.45	.30	+.60	.15	−.26	.50	+.94		+.11	.40
VS Per cent of carbon	+.23	.40	−.84	<.01	+.12	.80	+.11	.80	−.73	.08	−.57	.10	−.53		−.03	.85
VS Per cent of sulphur	+.69	.01	−.62	.06	−.06	.90	+.48	.30	−.02	.95	+.15	.70	−.87		+.19	.15
Per cent of residuum																
VS A.P.I. of residuum	−.63	.01	−.68	.03	−.69	.09	−.14	.80	+.03	.95	+.73	.02	−.34		−.34	.01
VS Per cent of carbon	+.74	<.01	+.79	. 01	+.96	<.01	+.85	.02	+.78	.04	+.94	<.01	+.98		+.26	.04
VS Per cent of sulphur	+.62	.01	+.77	.01	+.97	<.01	+.62	.15	+.56	.20	+.41	.30	+.95		+.55	<.01
A.P.I. residuum																
VS Per cent of carbon	−.77	.<01	−.92	<.01	−.78	.04	−.44	.30	+.04	.95	+.55	.12	−.46		−.08	.55
VS Per cent of sulphur	−.73	.<01	−.68	.03	−.77	.05	−.18	.70	+.10	.80	+.8	.80	−.92		−.27	.03
Per cent of carbon																
VS Per cent of sulphur	+.81	<.01	+.72	.02	+.94	<.01	+.60	.15	+.44	.30	+.32	.40	+.97		+.20	.15
Number of analyses used	15		10		7		7		7		9		4			

* $\sqrt{\frac{1}{n}\Sigma[(\text{A.P.I.})_a-(\text{A.P.I.})]}$ and $\sqrt{\frac{1}{n}\Sigma[(\text{per cent})_a-(\text{per cent})_b]}$.

† A.P.I. = A.P.I. gravity of a distillation fraction; per cent = the percentage content of that fraction; n = number of fractions used; a = any one of the mean analyses, and b of any other one of the mean analyses of the six depth-age groups, Tables I and II.

‡ Per cent = percentage content; A.P.I. = A.P.I. gravity.

§ r = Pearson product correlation coefficient, showing the degree of correlation between the variation of the two quantities; perfect correlation = 1.00. P = Probability factor showing the chance of that correlation being accidental; certainty = 1.00 In part II of the table ( ) = statistically only semi-significant. + or − = sign of correlation where the probability of the correlation is more than 2 out of 3.

	Miocene						Oligocene				Eocene				All Three Ages Both Depth Zones	
	3,000–5,000				5,000–7,000		3,000–5,000		5,000–7,000		3,000–5,000		5,000–7,000			
	Except Spindletop		Spindletop													
	r	*P*	*r*	*C*	*r*	*C*	*r*	*P*	*r*	*P*	*r*	*P*	*r*	*P*	*r*	*P*
II. Values Showing Significant or Semi-Significant Correlation																
Per cent light fractions																
VS A.P.I. of light fractions	+		−				−.78	.04			+					
VS Per cent of residuum	−.78	.01	+		−.92	<.01	−.82	.03	−		−.97	<.01			−.81	<.01
VS A.P.I. of residuum	(+.46	.09)							−.91	<.01	−.84	<.01			−.32	.01
VS Per cent of carbon residue	−.57	.03			−.80	.04	−				−.89	<.01				
VS Per cent of sulphur			(+.60	.06)	−.88	.01	−								−.40	<.01
A.P.I. of light fractions																
VS Per cent of residuum			−.79	.04					−		−					
VS A.P.I. of residuum			+.78	<.01			+		+							
VS Per cent of carbon residue			−.84	<.01					(−.73	.08)	−					
VS Per cent of sulphur	+.69	.01	(−.62	.06)			+									
Per Cent of residuum																
VS A.P.I. of residuum	−.63	.01	−.68	.03	(−.69	.09)					+.73	.02			−.34	.01
VS Per cent of carbon residue	+.74	<.01	+.79	.01	+.96	<.01	+.85	.02	+.78	.04	+.94	<.01			+.26	.04
VS Per cent of sulphur	+.62	.01	+.77	.01	+.97	<.01	+		+		+				+.55	<.01
A.P.I. Gravity of residuum																
VS Per cent of carbon	−.77	<.01	−.92	<.01	−.78	.04	−				+					
VS Per cent of sulphur	−.73	<.01	−.68	.03	−.77	.05									−.27	.03
Per cent of carbon																
VS Per cent of sulphur	+.81	<.01	+.72	.02	+.94	<.01	+		+		+					

TABLE XII

SUGGESTIVE CORRELATIONS BETWEEN PERCENTAGE CONTENT AND A.P.I. GRAVITY OF THE 200–250 DEGREE CENTIGRADE FRACTION AT ATMOSPHERIC PRESSURE AND OF RESIDUUM AND PERCENTAGE CONTENT OF CARBON RESIDUE AND SULPHUR

	Directly with	*No Correlation Suggested*	*Inversely with*
Per cent 200–250°C*	—	A.P.I. 200–250°(G)†	—
200–250°C	—	—	Per cent residuum (G)
200–250°C	—	—	A.P.I. residuum (P)
200–250°C	—	—	Per cent carbon (P)
200–250°C	—	—	Per cent sulphur (?)
A.P.I. gravity*	—	Per cent residuum (G)	—
200–250°C			
200–250°C	—	A.P.I. residuum (G)	—
200–250°C	—	Per cent carbon (G)	?
200–250°C	—	Per cent sulphur (G)	—
Per cent residuum	—	—	A.P.I. residuum (P)
200–250°C	Per cent carbon (G)†	—	—
200–250°C	Per cent sulphur (F)†	—	—
A.P.I. gravity residuum	—	—	Per cent carbon (P)
200–250°C	—	—	Per cent sulphur (F)
Per cent carbon residue	Per cent sulphur (P)†		

* $\sqrt{\frac{1}{n}\Sigma[(\text{A.P.I.})_a-(\text{A.P.I.})_b]}$ and $\sqrt{\frac{1}{n}\Sigma[(\text{per cent})_a-(\text{per cent})_b]}$.

† (G) = Good correlation; (F) = Fair correlation; (P) = Possibly this correlation.

oil deposits: (1) the theory of the migration of most oil upward from deep source beds into the oil sands in which it is now found; (2) the theory that the upward decrease of the A.P.I. gravity (increase of the specific gravity) of crude oil toward the surface is the effect of the evaporation of the light constituents; (3) the theory that the upward decrease of the A.P.I. gravity (increase of the specific gravity) of the crude oil toward the surface is the effect of chemical reaction with the oxygen and sulphates of the surface waters.

No denial is made by the writer that in places oil has migrated upward from deeper source beds into shallower sands, that in very shallow oil deposits not well sealed off from the surface, evaporation of the low boiling fractions may take place and produce a heavier crude oil, or that intimate exposure of crude oil to oxidation may reduce it to a tarry asphaltic mass. But denial is made of the general common occurrence of those phenomena. The fact of the presence of any one of these effects is a question for determination in the case of each particular oil. The data of this study give strong evidence against the general applicability of those theories to the crude oils of the Gulf Coast.

If the Gulf Coast crude oils in general were migrant oils from great depths: (a) the bulk of the oil presumably must have seeped upward along some sort of semi-open fracture or fault plane; and (b) minor quantities of oil may have seeped through formations across stratification or up within the edge of the salt; and, under case (a), oils of essentially identical character should be found at all depths and in sands of all ages; and, under case (b), theoretically, straining and fractionation of the oil should take place and the migrant oil should be lighter and less viscous than the parent oil; but it would seem in general that migration of large quantities of crude upward across stratification must in general take place along some sort of semi-open fissures rather than through the body of a formation or through salt at its edge.

The impossibility of the Miocene and Oligocene crude oils being migrant Eocene crude oil is proved by the striking differences between the two groups of crude oil (Tables I–VI). The A.P.I. gravity of each of the Hemphill distillations, except the residuum and the very low boiling fractions, is many degrees higher for the Eocene crude oils than for the Miocene and Oligocene crude oils of comparable depth; and is higher for the Eocene crude oils of the 3,000–5,000-foot zone than for the Miocene crude oils of the 5,000–7,000-foot zone. Drastic molecular differences exist, therefore, between the Eocene crude oils and the Miocene and Oligocene crude oils of comparable

depth and between the shallower Eocene crude oils and the deeper Miocene oils. The Eocene crude oils are more paraffinic and less naphthenic than Miocene and Oligocene crude oils of the same, shallower, or slightly greater depth. The ratios between the percentage content of the Hemphill distillation fractions are different for the Eocene crude oils and for the Miocene and Oligocene crude oils; and simple "evaporation" of lower boiling fractions will not reduce the composition of the Eocene crude oils in terms of the percentage content of the Hemphill distillation fractions to that of the Miocene or Oligocene crude oils (Table XIII). The oils which we find in Miocene and Oligocene oil sands, in general, decisively are not migrant Eocene crude oils, which have undergone no change or only slight change in character during their migration.

TABLE XIII

RECALCULATION OF PERCENTAGE COMPOSITION OF DEEP OIL UNDER THEORY OF MIGRATION AND EVAPORATION

Depth Zone Feet	*3,000 to 5,000*	*5,000 to 7,000*	*3,000 to 5,000*	*5,000 to 7,000*	*3,000 to 5,000*	*5,000 to 7,000*
Distillation Range	I	II	III	IV	V	VI
Atmospheric Pressure	*Miocene*		*Oligocene*		*Eocene*	
75–100	0.2	Assumed same as in I	0.6	Assumed same as in III	1.9	Assumed same as in V
100–125	0.7		1.0		4.4	
125–150	0.8		1.0		4.3	
150–175	1.1		3.9		4.5	
175–200	3.3		3.6		5.0	
200–225	5.4		6.2		5.8	
225–250	8.1		9.0		8.1	
250–275	11.8		13.4	13.3	10.4	10.4
40 Millimeters Pressure						
0–200	8.2	9.6	8.5	8.2	7.3	10.5
200–225	9.8	9.9	9.6	9.3	7.2	10.4
225–250	8.1	8.7	7.6	7.5	6.8	8.2
250–275	7.5	7.0	7.0	6.6	6.2	6.5
275–300	8.5	8.3	7.7	7.8	6.8	6.7
Residuum	26.4	25.0	20.9	21.9	21.0	10.9

Analyses I, III, and V are taken directly from Table I. In II, IV, and VI, the respective percentage contents of the heavier half of the cuts have the same ratios as in the corresponding oils of Table I, but have been recalculated so that the sum of the fractions 250–275 degrees Centigrade atmospheric pressure to residuum inclusive = 100 per cent minus the percentage sum of the fractions 225–250 degrees Centigrade atmospheric pressure and more volatile.

The impossibility of the Miocene crude oils being migrant Oligocene crude oil is suggested, but not clearly proved by the data. The differences between the character of the two groups of crude oils

are slight and do not decisively preclude the migrant derivation of the Miocene crude oils from the Oligocene crude oils.

The shallower oils, in general, can not be migrant deep oils which have undergone no change or only slight change in the migration, for the two groups differ both in their composition in terms of the percentage composition of the Hemphill distillation fractions, and in the A.P.I. gravity of the corresponding Hemphill distillation fractions and therefore in the molecular character of those fractions. The difference in the character of the base is most striking: the shallower oils predominantly are naphthenic; and the deeper oils are of intermediate base well toward paraffinic.

The probable absence of much vertical migration at Spindletop, Jefferson County, has been shown by the writer in a study of an extensive series of United States Bureau of Mines analyses of crude oil from that dome.[8] Four distinctively different crude oils are represented among the analyses: one type is found in the cap rock and the other three are found at successively deeper stratigraphic horizons on the flank. No one of the four types can be migrant crude of another type unless drastic molecular change has taken place in the oil. A fifth type is surmised to be present slightly above the shallowest of those three flank crudes, but is not represented in that series of analyses. The cap-rock crude oil necessarily is migrant oil and is surmised to be migrant oil of that fifth type.[9] Minor vertical migration can be recognized, but, in the main, much vertical migration across stratification seems definitely not to have taken place. Evidence against the formation of prolific oil deposits by extensive vertical migration in one oil field, of course, is not evidence against the common formation of oil deposits by vertical migration elsewhere. But the occurrence of oil at Spindletop is of a type which commonly is explained by upward vertical migration of deep-seated oils across stratification or along the edge of the salt. The decisive evidence against much vertical migration of crude oil at Spindletop, therefore, is significant.

The impossibility of the general derivation of the shallower from the deeper crude oils by fractionation during migration is shown by the much higher percentage content of high boiling fractions, and greater viscosity in the shallower crude oils. Crude oils are found on the Gulf Coast which would seem to have formed by fractionation during migration and the consequent straining out of the more viscous

[8] Donald C. Barton, "Variation and Migration of Crude Oils, Spindletop, Jefferson County, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 19, No. 5 (May, 1935), pp. 618–43, 3 figs.

[9] The caprock oil at Spindletop is shown by a study now in progress to belong to a very distinctive type of crude that is found in the Upper Miocene at depths of 1,500–2,500 feet in southeast Texas and southwest Louisiana.

fractions. At Belle Isle, St. Mary Parish, Louisiana, the oil recovered from the top part of the salt core is light enough to be used in kerosene lanterns; only dubious reports of oil shows are logged from the deeper, flank wells; the oil in the salt, therefore, seemingly must have seeped up through the salt mass from considerable depth; and in that migration, it underwent fractionation. But such light oils are rare among the shallow Gulf Coast oils and, therefore, on the whole, the shallow oils of the Gulf Coast seemingly can not be crude oils which have migrated across stratification for considerable distance.

ARGUMENT AGAINST "EVAPORATION" THEORY

The "evaporation theory" will not account for the observed variation of the Gulf Coast crude oil with depth, for the shallow crude oils definitely are not deep, light crude oils which have become heavy because of evaporation of their lower boiling fractions. The shallower crude oils in the first place have a lower A.P.I. gravity (higher specific gravity) fraction by fraction than do the deeper oils of the same or greater geologic age, and, therefore, have a different molecular composition. Simple evaporation without drastic molecular change will not transform the deeper oils into the shallower oils. The composition of the shallow crude oils in terms of the lubricating and heavier fractions (fractions which boil above 275° Centigrade at atmospheric pressure) gives partial evidence against the "evaporation theory." Recalculation of the composition of the mean crude oils of the deeper zone is attempted in Table XIII on the assumption that evaporation of the lighter fractions takes place until the respective contents of the Hemphill fractions boiling over below 275 degrees Centigrade at atmospheric pressure is the same as in the mean crude oil of the same geologic age in the shallower zone; the oils of all three ages from the shallower zone clearly can not be migrant Eocene crude oil from the deep zone; and the Miocene crude oil from the shallower zone can not be migrant Oligocene crude oil from the deeper zone. From the percentage composition alone, however, the deeper Miocene crude of Table XIII can not be distinguished from the shallower; and the deeper Oligocene can not be distinguished from the shallower. But in those cases, the difference between the specific gravity of the corresponding Hemphill fractions is sufficient to show that the crude oils of the shallower zone can not be migrant oils of the same age from the deeper zone, unless drastic molecular change has taken place in the character of the oil.

ARGUMENT AGAINST "OXIDATION" THEORY

The theory of "oxidation" would seem to be questioned by the experiments by the United States Bureau of Mines on drastic oxida-

tion.[10] Four crude oils, ranging from naphthenic to paraffinic, were subjected to drastic oxidation. The resulting reaction consisted in the formation of insoluble products which immediately dropped out of solution without essential change in the percentage composition of the crude oil, and with a decrease of a small fraction of a degree in the A.P.I. gravity (increase of the specific gravity) of each of the fractions. Laboratory experiments rarely duplicate natural conditions; and too much weight perhaps should not be given these experiments; and the slow oxidation through the enormously greater lengths of geologic time might or might not produce a different result.

GENERAL ARGUMENT AGAINST "SURFACE INFLUENCE"

The following argument is decisive. Unlike the arguments in regard to oxidation and evaporation, its validity would be unaffected by error or inadequacy in present-day theory in regard to reactions. The argument, briefly, is as follows.

1. The effect of any factor working from the surface downward must be proportional inversely to depth below the surface and directly as the length of exposure.

2. The oils in the older rocks in general must have been in them for a longer time than the oils in younger rocks. This postulate predicates, for example, that some oil was formed or migrated into the Eocene beds of the Gulf Coast before Miocene time; that no oil could form in, or migrate into, the Miocene beds until they had been laid down; and that, therefore, oil in the Eocene beds on the average must be older than oil in the Miocene beds.

The possible exception to this postulate is for all the oil in all the formations to have formed in them, or come in, after the deposition of the youngest oil-bearing formations.

This postulate definitely does not imply that every crude oil in a younger rock is younger than every crude oil in an older rock.

3. The shallower Oligocene and Eocene oil sands have never been buried to depths very much greater than those at which they now lie. The structural relief of the non-salt-dome oil fields of the Gulf Coast is small; and the evidence does not suggest the cumulative erosion of more than hundreds of feet from above those oil fields. Slightly more uplift has taken place around the shallow salt domes than in the non-salt-dome oil fields, but much of that apparent uplift presumably is the effect of the subsidence of the beds far out from the salt core rather

[10] S. S. Taylor and H. M. Smith, "Summary of Experimental Data on Laboratory Oxidation of Crude Oils, with Particular Reference to Air-Repressuring," *U. S. Bureau of Mines Report of Investigations, 3238* (May, 1934), 11 pp.

than of actual uplift of the salt core and of the beds adjacent to it.[11]

4. If this surface factor tends to produce heavier crude oils and if the original crude oils were all approximately of the same character, the order of heaviness of the crude oils would be:

Heaviest

(1) Shallower Eocene crude oils, on account of stronger influence × longest time
(2) Shallower Oligocene crude oils, on account of stronger influence × 2nd longest time
(3) Shallower Miocene crude oils, on account of stronger influence × shortest time
(4) Deeper Eocene crude oils, on account of weaker influence × longest time
(5) Deeper Oligocene crude oils, on account of weaker influence × 2nd longest time
(6) Deeper Miocene crude oils, on account of weaker influence × shortest time

Lightest

The relative position of 3 and 4, and the closeness of each to 2 and 5 can not be determined without knowledge of the ratio of the influence of time to that of depth

5. If a "depth" factor is assumed, that is a factor whose effect is proportional to depth and age, and whose influence is in the direction of producing a lighter crude oil, then the order of heaviness would be:

Heaviest

(1) Shallower Miocene, on account of lesser influence × shortest time
(2) Shallower Oligocene, on account of lesser influence × 2nd longest time
(3) Shallower Eocene, on account of lesser influence × longest time
(4) Deeper Miocene, on account of greater influence × shortest time
(5) Deeper Oligocene, on account of greater influence × 2nd longest time
(6) Deeper Eocene, on account of greater influence × longest time

Lightest

The relative position of 3 and 4 and the closeness of each to 2 and 5 can not be determined without knowledge of the ratio of the effects with time and with depth

If the influence of the "depth" age factor were in the direction of producing a heavier oil, the order of heaviness, of course, would be reversed.

The observed variation of heaviness in the Gulf Coast crude oils has been seen to conform to the following order of heaviness:

Heaviest

(1) Shallower Miocene
(2) Deeper Miocene and shallow Oligocene
(3) Shallower Eocene and deep Oligocene
(4) Deeper Eocene

Lightest

This order is that which would be produced by a "depth influence" and is inconsistent with that which would be produced by a "surface factor." This argument, therefore, is a decisive one against the explanation of the observed increase of lightness with depth on the basis of oxidation or evaporation, or of any other influence which works from the surface downward

[11] Donald C. Barton, "Mechanics of the Formation of Salt Domes with Special Reference to Gulf Coast Salt Domes of Texas and Louisiana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 9 (September, 1933), pp. 1025 to 1083, 9 figs.

EVOLUTIONARY TRANSFORMATION INTUITIVELY EXPECTABLE

Natural intuition leads to the expectation of evolution of the Gulf Coast crude oil from naphthenic to, or toward, paraffinic, as the effect of temperature, pressure, and time. High temperatures and high pressures prevailing for a short time in the refinery are known to produce drastic changes in the character of petroleum. Under ground, the pressures are comparable at great depth; the temperatures are lower; but the lengths of available geologic time are enormous; and the effects of extremely slow reactions may be considerable. Intuitively, therefore, some sort of change in the character of crude might be reasonably expected to be inevitable, as the effect of temperature, pressure, and time. Reactions in petroleum refining take place much more rapidly at high, than at low temperature; and, therefore, the effects of reactions at great depth expectably should be greater than those at shallow depth. The naphthene-base crude oils have the more complex molecules and in general are the less stable; whereas the paraffine-base crude oils have the simpler molecular structure and the more stable. Evolution from naphthenic to paraffinic, as an evolution from complex and less stable to simpler and more stable, therefore, might be expected, intuitively, as the direction, or a direction, of those reactions under the influence of time, temperature, and pressure.

A systematic tendency toward a general law of variation of Gulf Coast crude oil has been found both by the preceding study and by the present study. The variation consists in: (a) increase in the percentage content of the lower boiling (lighter) fractions and decrease in the percentage content of the higher boiling (heavier) fractions with increasing depth and age; (b) increase of the A.P.I. (Beaumé) gravity (decrease of the specific gravity) of all fractions of the crude oil with increasing depth and age; and (c) progressive shift in the character of the base of the crude oil from naphthenic in the shallower younger oils almost to paraffinic in the deeper, older oils. This variation has been seen to be inconsistent with any reaction proportional to age and nearness to the surface and to be consistent with a reaction proportional to depth and age. The observed systematic variation, therefore, would seem to be the variation which intuitively should be expected.

CAUSE OF THE EVOLUTION

Increase in the ratio of hydrogen to carbon presumably is involved in that observed variation. Carbon, therefore, must be lost; or hydrogen must be added, or both. Increase in the hydrogen-carbon ratio is accomplished in the refinery either by adding hydrogen, (a) to all of a charge of crude oil by the addition of hydrogen from an outside

source (hydrogenation), or (b) to part of a charge by robbery of hydrogen from the rest of the charge (cracking). Two end products, therefore, are produced by cracking, the one lighter, and the other heavier than the original charge. But in the evolution of the Gulf Coast crude oil, the percentage content of the residuum decreases and the A.P.I. gravity increases (specific gravity decreases); no accumulation of heavy end products has taken place within the crude oil as the result of its evolution. Dead asphaltic material is reported only rarely, and in small quantity, in the Gulf Coast. If the reaction which produced the evolution of the crude oil were in the main cracking, and if the lighter products were fractionated off from the heavier ends, those complementary heavy crude oils should be approximately as common as the light oils, but definitely are not. That reaction, presumably, therefore, in the main can not be cracking.

Loss of carbon might be accomplished by a reaction between the crude oil and water, resulting in the production of CO_2 and the addition of hydrogen to the crude oil. Dissemination of considerable quantities of water through oil sands as the filling of the smaller openings and as film around the sand grains is being recognized as common. That minute dissemination of water through the crude oil should greatly favor any such reaction if it is chemically possible. Carbon dioxide, or monoxide, however, has not been reported in association with the Gulf Coast oil deposits. Secondary calcareous cementation of sand and gravel is rather common around the shallow domes, but is not common in the same degree in the blanket sand oil fields over the deep salt domes; and, therefore, any hypothesis involving the generation of CO or CO_2 seems geologically improbable, but not wholly impossible.

The only other plausible source of hydrogen would seem to lie in natural gas, and therefore, largely in methane. According to a common intuitive explanation, the natural gas so commonly associated with oil deposits is regarded as having been given off by the crude oil. Some natural gas probably may have formed in that way. But much or most of the methane seemingly might form independently of, although perhaps contemporaneously with, the crude oil. Methane is known to form easily from a wide range of organic material. We do not know as yet just what organic material serves as the mother material for petroleum, but we may surmise that methane is formed from certain types of organic material and petroleum from other types, or from a lesser range of types, of organic material than the methane. We do know that methane forms under conditions under which, as far as we can detect, petroleum does not form; as, for ex-

ample, in marsh deposits and in coal deposits. Methane might also form in the first dissolution process, in which the original organic material would go over into methane, proto-petroleum, and possibly other products. The laws of accumulation for methane are essentially the same as those for the accumulation of crude oil.

Methane formed independently of crude oil, therefore, might accumulate with it and provide an independent supply of hydrogen. The methanation theory involving an indirect hydrogenation through a reaction between methane and crude has been proposed by Pratt[12] to explain the evolution of the Gulf Coast crude oil, which was postulated by the writer in his earlier study. The direction of the reaction: generation of methane from crude oil—combination of methane with crude oil—presumably might depend on the mass law; and if present in less than some certain ratio, methane would be formed from the crude oil; and if present in excess of that ratio, the methane might tend to combine with the crude oil. The results of the present study lend additional support to the theory of methanation as the main, but not necessarily the only, reaction in the observed evolution of the Gulf Coast crude oil under the influence of pressure, temperature, and time.

FULL LAW PROBABLY MORE COMPLICATED

The full law of the evolution of crude oil under the influence of time and the depth linked factors, temperature and pressure, may be more complicated than the simple law which has been stated for the Gulf Coast crude oils. The law of decrease of the specific gravity with geologic age seems not to apply, for example, or to apply only partially, to the very low boiling fractions; and the law of decrease of specific gravity with depth applies to those very low boiling fractions only with exceptions. The general applicability of the law of decrease of the specific gravity of the Hemphill distillations to all the crude oils of the United States is indicated by a new study which the writer has in progress. On the other hand, two exceptions seem to be indicated: (1) by the Ordovician crude oils of Texas and Oklahoma, and (2) by the Pennsylvanian crude oils of one district. Several alternative courses would *a priori* be possible for the later stages of this evolution of crude oil: (a) the evolution may continue indefinitely until the whole mass of the crude oil has been transformed into very low boiling, or gaseous, fractions, and has been dissipated; the absence of commercial oil deposits in association with carbon ratios of more than 65 per cent may represent such a trend to this law of evolution; such a

[12] Wallace E. Pratt, "Hydrogenation and the Origin of Oil," *Problems of Petroleum Geology*, American Association of Petroleum Geologists (1934), pp. 235–45.

trend to the law might prove inconsistent with the methanation theory of explanation of it, unless sufficient quantities of methane are available until the end; (b) the evolution may be asymptotic to some ultimate type of paraffinic crude oil, whose character might vary somewhat under different conditions; the evolution would take place most rapidly at the greater depths during its earlier stages, and at the shallower depths during the later stages; and ultimately very old, shallow oils might reach essentially the same stage of evolution and essentially the same character as the very old deep oils; the lack of variation of the Ordovician crude oils with depth may be an expression of the latter trend of the law; (c) if dependent upon methanation, the evolution for each deposit might be asymptotic to the character of the particular crude oil when some critical ratio of paraffinicity to methane is reached; (d) the evolution might be dependent upon more than the methanation reaction, or than any other single type of reaction; and the final trend might be a confused one, only partially toward an asymptote. Limitation of the law of increase of lightness with depth to the naphthene-base crudes in contrast to the paraffine-base crudes has been suggested by Krejci. No such limitation seems to hold in general, according to the results of a study just begun by the writer, if the conventional sample division is made of the base of the crude oil into naphthenic and paraffinic. But if the United States Bureau of Mines' recent, much sharper division of the base of crude oils (paraffinic, paraffinic intermediate, intermediate paraffinic, etc.) is used, that study has not progressed far enough to determine whether or not that limitation applies to the paraffinic-paraffinic crude oils.

OTHER LAWS OF VARIATION

Other laws of variation than this evolution of lightness with increasing depth and age produce changes in the character of crude oil. A most important one of those laws of variation is the tendency toward the stratification of crude oil according to specific gravity within individual reservoirs. Ventura Avenue, California, has been cited as a clear contradiction of the writer's law of decrease of specific gravity—increase of A.P.I. gravity with increasing depth. Kettleman Hills and practically every oil field in which the vertical dimension of the oil reservoir is large might also have been cited. But in these cases we are dealing with a law which has to do with variation in the character of petroleum within a reservoir and not between reservoirs, whereas the law of increase of lightness with depth applies between reservoirs. They are two different laws of variation and neither one precludes or contradicts the existence of the other. The effects of the

one in the one place may mask, and in another place be masked by the effects of the other. Every oil field in a district (if a single reservoir) might show decrease in the lightness of an oil with increasing depth. And yet the plotting of depth against the mean character of the crude oil of each oil field could at the same time show progressive increase of lightness with depth. The relations of the heavy Pennsylvanian oils and of the lighter Cretaceous oils of the Rocky Mountains might be cited as a brilliant contradiction of the law of evolution of lightness with increasing age. The citation of individual occurrences such as Ventura Avenue, Kettleman Hills, and the Pennsylvanian oils of the Rocky Mountains, can not disprove the law of evolution of lightness with increasing depth and age, but does prove the existence of other laws of variation of the character of crude oil. The proof or disproof of the applicability of the law of evolution of lightness with increasing depth and age to a particular district can be obtained only by taking the data regarding crude oil from a statistically considerable number of oil fields and from a considerable range of age and depth and by plotting the character of the crude oil against depth by the respective ages, and the character of the crude oil against age of respective depths. Much scattering will be produced by the other factors which affect the character of the crude oil. And if the range of depth or of age of the samples is too small, the scattering may obscure the respective effects of depth and age; and if data are available in regard to a few samples of crude oil, the scattering will give chance for a wide range of combinations which give apparent but meaningless correlation between depth or age and the variation of the petroleum. In discussion of the causes of the variation of crude oil, it is most important to remember that the character of crude oil presumably must be a function of many variables. Great care must be taken that the effects of one variable are not confused with, or obscured by, the effects of another; and the statistics in regard to the variation of crude oil must be handled with care in order to evaluate the effects of a particular variable.

RECAPITULATION

The respective mean characters of Miocene, Oligocene, and Eocene Gulf Coast crude oils from depths of 3,000–5,000 feet have been compared with those of equivalent age from depths of 5,000–7,000 feet.

A tendency toward a systematic variation of character with depth and age is present and consists: (a) in a progressive change in the base of the crude from naphthenic to intermediate, and almost to paraffinic in the deep Eocene crude oils, with increasing depth and age of the

crude oil, and (b) in an increase in the percentage content of the lower boiling fractions of the crude oil with increase of its depth and age.

The observed variation in the character of the crude oil gives trenchant evidence against theories of the origination of the shallow crudes through the migration of deep light crude and through oxidation, or other chemical reactions, through evaporation of the lower boiling fractions, or through any other factor working from the surface down.

The order of variation in the character of the crude oil with depth and age is consistent with alteration of a heavy crude oil into a much lighter crude under the influence of time and some factor or factors linked with depth below the surface and is inconsistent with the alteration of a light crude into a heavy crude under the influence of time and some factor or factors working from the surface down.

The theory is advocated, therefore, that the respective ancestral crude oils of all the crude oils of the Gulf Coast were heavy naphthenic oils, and that transformation of the character of crude oil has taken place in proportion to depth and to age, and that the transformation consists both in the decrease of the specific gravity of the individual fractions in the consequent change in the base from naphthenic toward paraffinic, and in the increase in the percentage content of the lower boiling fractions.

The observed evolution of the Gulf Coast crude oil involves decrease of the ratio of carbon to hydrogen.

The data are against cracking as the main reaction in that evolution. Pratt's methanation is regarded as the most plausible reaction to explain the evolution.

This particular law of evolution of crude is only one of many laws of variation of the character of crude oil. Citations of individual occurrences contradictory to this law of variation of crude oils do not necessarily disprove this law but may be proving one of the other laws of variation.

The statement of the law as induced from the variation of crude oil in the Gulf Coast may be an incomplete, merely approximate statement of a more complicated law.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 21, NO. 7 (JULY, 1937), PP. 947-958, 7 FIGS., 1 PLATE

GEOLOGICAL NOTES

LA BLANCA STRUCTURE, HIDALGO COUNTY, TEXAS

The La Blanca structure, located in central-eastern Hidalgo County, approximately 7 miles northeast of Edinburg, county seat, was proved productive when the Pantano Petroleum Company and Speed Oil·Company's R. E. Harding No. 1, Lot 11, Block 94, Missouri-Texas Land and Irrigation Company Survey, blew out, caught fire, and cratered on October 5, 1936, while coring a fifth saturated sand at 7,820–7,840 feet in Frio topped at 5,180 feet. This well burned for 2 months.

This structure was originally discovered and mapped in detail by the McCollum Exploration Company by reflection seismic work during 1935. The area was blocked and farmed out to the Quintana Petroleum Company, who in turn drilled Engelman No. 1, Lot 10, Block 94, Missouri-Texas Land and Irrigation Company Survey, to a depth of 8,883 feet during the spring of 1936. This well logged numerous sections of thick sand with petroleum taste and odor in the Frio, but was abandoned when the drill stem became stuck after an attempted blow-out, killing an official of the operating company as a result of the derrick being pulled in. The well topped markers as follows according to the Humble Oil and Refining Company paleontologic determinations.

	Feet	
Fleming to	4,013	
Catahoula	4,023–4,868	
Fossil zone	4,868–5,206	(*Discorbis candeina* 4,878)
Frio	5,206–8,805	
Vicksburg	8,805–8,883	
Total depth	8,883	

The most common fauna reported in the fossil zone are:

Discorbis candeiana
Elphidium poeyanum
Elphidium chipolensis
Rotalia beccarii
Ostracods (undifferentiated)
Oysters (undifferentiated)

These fossils indicate shallow-water deposition. Lithologically the fossil zone is composed of greenish gray sand and sandy clay, reddish brown sandy clay, olive-green sand with calcareous nodules included, and sandy clay.

Since the drilling of these two wells, three producers have been completed, all running practically level on sub-sea elevations.

1. Pantano Petroleum Company and McCollum Exploration Company's J. C. Engelman, Jr. No. 1, Lot 8, Block 259, Texas-Mexican Railway Survey, was drilled to 6,805 feet and completed in sand 6,666–6,683 feet, making 80 barrels of 59° gravity crude with casing pressure of 2,350 pounds, and tubing pressure of 2,175 pounds.
2. Pantano Petroleum Company and McCollum Exploration Company's James McDougal No. 1, Lot 1, Block 223, La Blanca Subdivision of Rio Grande Land and Irrigation Company, was drilled to 8,070 feet and completed in Frio sand at 7,840–7,891 feet, with perforation 7,867–7,875 feet for 148 barrels daily on $\frac{5}{8}$-inch choke. Tubing and casing pressure is 3,400 pounds.
3. Sterling Oil and Refining Company completed J. C. Engelman, Jr. No. 1, Lot 5, Block 95, Missouri-Texas Land and Irrigation Company Survey in the McDougal sand for approximately 125 barrels daily on small choke. The well tested good saturation in the 7,500-foot sand section found in the McDougal well from 7,501 to 7,559, but passed up in both wells.

To date, the five wells drilled have encountered the deeper sands at approximately the same level, revealing a large domal uplift elongate to some extent on a northwest-southeast axis. The west and southwest sides, as interpreted from geophysics, reveal steep reverse dips, thus making the uplift asymmetrical. Faulting is believed to exist on the north, west, and south flanks. The structure is thought to have approximately 400 feet of closure in the middle Frio with less structure being found above, thus indicating possible pre-Catahoula uplift.

Schlumberger surveys run on wells to date reveal good sands carrying oil and gas in four sections ranging in depth from 6,600 feet to 8,040 feet, the total depth to which such electrical surveys have been made. Average porosity is 23 per cent with an average horizontal permeability of 550 millidarcys. The total sand thickness between 7,500 feet and 8,070 feet averages 200 feet, and cores extracted from sand sections reveal good saturation of high-gravity oil. Wells completed in the 7,850–7,900-foot sand have a shut-in pressure of 3,400 pounds, casing and tubing pressure at the well-head, with bottom-hole pressure of approximately 4,000 pounds at 7,600 feet.

Cheap fuel, abundance of irrigation water, and thick sandy shales, make for reasonable drilling costs.

This structure will probably produce from the Vicksburg and Jackson, as both are thought to lie within present drilling depths.

The La Blanca structure, third producing field to be discovered in Hidalgo County within the past 3 years, lies between the Samfordyce field, 30 miles updip, and the Shell Petroleum Corporation's Yturria No. 1, La Sal Vieja prospect, Willacy County, 15 miles downdip. The Yturria No. 1, which produced from the Frio, flowed about 5 months, and is now being deepened. The La Blanca field is 9 miles up the strike and approximately 900 feet updip from the Union Sulphur Company's Mercedes field, Hidalgo County. Samfordyce, La Sal Vieja, Mercedes, and La Blanca all have yielded production

from the Frio. The Samfordyce and Mercedes structures have faults of considerable throw. More drilling will be required on La Blanca before fracturing in the Frio can be established, although faulting is suspected.

CARLETON D. SPEED, JR.

SECOND NATIONAL BANK BUILDING
HOUSTON, TEXAS
May 4, 1937

STAINING DRILL CUTTINGS FOR CALCITE-DOLOMITE DIFFERENTIATION

While studying various samples of dolomite, dolomitic limestone, and dolomite marble, the writers naturally needed to identify the constituent minerals and to determine the grain relationships between them. One of the most satisfactory ways to do so is to grind plane-surfaced sections of the rock and stain them with a substance which stains selectively one of the other minerals. The value of this technique was notably demonstrated by Steidtman,[1] who used the time-honored Lemberg solution and others in his work.

The writers, however, apparently had more difficulty with the Lemberg solution staining than Steidtmann did, but found a staining method recently suggested by Fairbairn[2] to be more satisfactory in their hands. Others, no doubt, will welcome familiarity with the technique. Since Fairbairn's paper probably will not be generally read by many geologists whose work is along other lines, but who may be in need of the information on the stain used at Innsbruck, a discussion of it follows.

Two solutions are used, the first being ferric chloride made up in water to about 2½ per cent strength (Fairbairn does not give the concentration he used), and the second, ammonium sulphide $(NH_4)_2S$ which has been saturated with H_2S. A pan of water or running source is also needed.

The rock specimen, either freshly broken or with its surface freshly ground, is first wet with water, then immersed for 5–10 seconds in the $FeCl_3$ solution, and next thoroughly washed and rinsed in water to remove all free $FeCl_3$. Holding it under the faucet for a few seconds serves very well. A second immersion in the $(NH_4)_2S$ solution for about the same length of time, followed by a second water rinse to remove excess chemicals, completes the treatment. The calcite stains

[1] Edward Steidtmann, "Origin of Dolomite as Disclosed by Stains and Other Methods," *Bull. Geol. Soc. America*, Vol. 28 (1917), pp. 431–50.

[2] H. W. Fairbairn, "Introduction to Petrofabric Analysis," p. 31, mimeographed copy, Queen's University, Kingston, Canada.

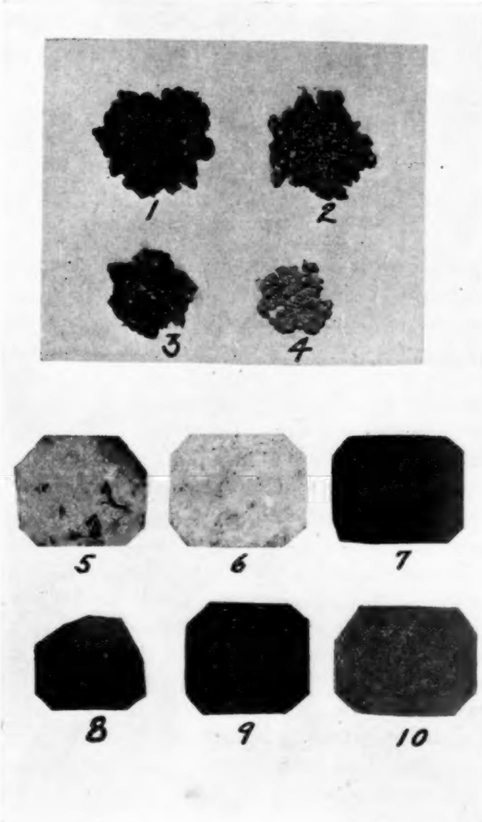

PLATE I

1. Burlington limestone drill cuttings. Some chert. Missouri
2. Jefferson City dolomite. Some calcite. Missouri
3. Chouteau formation. Some chert. Missouri
4. Potosi dolomite. Missouri
5. Gasconade dolomite. Some calcite. Missouri
6. Dolomite marble. Minute specks of calcite. New York
7. Burlington limestone. Missouri
8. Louisiana limestone. Dolomite band. Missouri
9. Jefferson City dolomite. Mottled carbonate. Missouri
10. Jefferson City dolomite. Missouri

black (see Plate 1, specimen No. 7), whereas the dolomite is unaffected and retains its original light color (No. 6). Very minute specks and intergrown angular grains of calcite are accurately, vividly, and distinctly marked, as shown in specimens Nos. 6 and 5. Confirmation was made a number of times as to the fidelity of the staining by testing the carbonate with *HCl* and the results were found to be wholly reliable.

No discussion of the reactions involved has been given, but probably the effect is caused as follows. Ferric chloride hydrolyzes into ferric hydroxide and hydrochloric acid. The acid formed in hydrolysis equilibrium is weak and therefore attacks calcite but not dolomite. Neutralization at the calcite surface causes deposition of iron hydroxide thereon, and this is stained to black iron sulphide by the ammonium sulphide. About the only precautions necessary are that the specimens be clean (free from grease or any obstructing material) and that account be taken of any ferric chloride which may penetrate and be held interstitial to the grains.

Drill cuttings can be tested by the same technique. A small sample may be held in a wire basket while being immersed, or the cuttings may be covered with the solutions in a beaker and the washing done by decanting with water.

Partial dolomitization is shown by partial staining. Chert in cuttings remains white and unstained, except, of course, where it contains calcite (Nos. 1, 2, 3). The technique has to recommend it the fact that staining occurs very quickly, vivid contrasts in color are developed, and all parts of a sample of cuttings are tested at once so that percentages may be estimated.

W. D. Keller
George E. Moore

University of Missouri
Columbia, Missouri
May 11, 1937

RETREAT AND ADVANCE OF CONNATE WATER AS A THEORY OF OIL AND GAS ACCUMULATION

The writer has been requested to submit for this ***Bulletin*** a brief outline of a paper which he recently published in an oil-trade journal.[1]

The essence of the theory is to the effect that orogenic movements of uplift and depression in and around sedimentary basins have caused connate waters to recede and subsequently advance through their re-

[1] "Theory of Oil and Gas Accumulation by Retreat and Advance of the Salt-Water Table," *The Oil Weekly* (April 12, 1937).

spective horizons. In this process, salt-water "drives" have occurred of a similar nature to artificial flooding of oil sands to accumulate oil in front of advancing water sheets.

Presumably, the recession of water in any carrier bed would represent a negative effect, or nearly so, on accumulation of fluids and gases of a lighter nature existing at the time in that horizon; but an advancing water front would give a pushing and gathering effect ahead of it. The geologic history of the various sedimentary basins and sides of uplifts indicates, by unconformities, that the strata have at times been raised sufficiently to drain connate waters downdip to adjust themselves to contours of lower level. The unequal hydrostatic pressure at a point of maximum uplift would, under these circumstances, adjust itself by drainage to points of lesser pressure on the artesian principle of movement. Salt water might recede to a lower level in some far removed position, or even drain to outcrop on the opposite side of a basin, thus lowering the water table. Even without such downdip drainage, the uplift might raise the carrier bed above the level of adjusted water pressure and thus leave some area without connate water under hydrostatic pressure, just as an island is raised above sea level. Time is unlimited in such processes. Manifestly not all the water in a carrier bed would be drained downward to the top of the water table but the free-moving water would fall back and only wet sands would remain. It is believed that any disseminated oil particles and gas bubbles would remain in the wet sands without notable pressure. At some later period when submergence ensues, the connate water advances through the carrier bed and thus produces a water drive to accumulate oil and gas under any structural traps which exist ahead of the moving water front. The lighter fluids and gases would be in the form of belts or strips as they were gathered ahead of the advancing water front. The width and amount of such oil and gas accumulations would vary with the origin factors and they might be concentrated in varying forms and positions. Some structural trap might be in a wrong position to receive accumulation even though it might contain abundance of sand and receive abundance of water in the process. The oil drive, while advancing, may have missed certain traps even though water later closed in on them behind the water front. Various combinations might ensue to explain the barrenness of oil and gas under certain structures in certain sands even though all the proper factors and circumstances may be present to fit the old theory of oil and gas accumulating updip through differential gravity. It is clear, on the water-drive theory of accumulation, that any structure that post-dates the drive would be relatively too

young to receive accumulation. Even an older structure that pre-dates the drive might be passed up in the irregularities of the process in so far as some well established zone of circulation is concerned but have caught accumulation in some deeper or shallower carrier bed.

Twenty years ago, M. J. Munn maintained that the old idea of oil and gas accumulating updip by differential gravity did not fit the physical facts adverse thereto and he drew the conclusion that water advancing downdip from the outcrop had gathered oil and gas ahead of it, as he stated in conversation. It would seem that such an idea presupposes not only the lack of connate water in the carrier beds but the presence of much fresh or brackish water associated with oil and gas fields; it may apply in exceptional cases. However, the writer believes the idea was correct in assuming that oil and gas do not accumulate updip through carrier beds due to their lighter gravity. The fact that a hole full of water in a well prevents either oil or gas from rising to the surface seems sufficient cause for discarding that theory. Buoyancy does not overcome the friction under equalized hydrostatic pressure.

It is possible that just as the sea has withdrawn from some epicontinental area or basin and subsequently advanced over the same area, due to water seeking its level, just so has the connate water in a carrier bed withdrawn to its subsurface sea and subsequently advanced in or into the basin. This may have been much more of a far-traveling process than one would at first surmise. Judged from letters and personal conversation with several petroleum geologists since publication of the writer's former article, the water-drive theory seems to meet with a considerable measure of favor.

Whether oil and gas are indigenous or secondary in a carrier bed, the same problems ensue as to their accumulation. We know that they exist in quantity in some structural traps and are practically absent in others of like nature, as exceptions. Some geologists think that both origin and accumulation are local. But it seems that the natural water-drive theory based on orogenic movements deserves the especial attention of research students with proper laboratory equipment to test it in line with the geological record and structural history of respective oil and gas provinces.

With the premise in mind that connate waters have retreated and advanced with orogenic movements, the writer is inclined to accept many of the principles of accumulation advocated during the past 16 years by John L. Rich.[2] Had this thought occurred to him when he

[2] See "Rich, John," *Comprehensive Index of the Publications of American Association of Petroleum Geologists* (1937).

was writing various papers on his hydraulic theory, many of his data could have been fitted into it with consistency and a better argument made for long-distance migration. The writer is wedded to no particular theory and has himself argued pro and con on the subject of local and distant accumulation. It is probable that by such processes of reasoning in connection with mechanical, physical, and chemical experiment, some satisfactory conclusion will ultimately be reached. Moreover, some practical implications are likely to arise from it in the search for oil and gas fields.

JAMES H. GARDNER

TULSA, OKLAHOMA
May 22, 1937

CRETACEOUS DEFORMATION IN KANSAS

Surface faults are rare in Kansas. This statement applies especially to the Paleozoic rocks. In the Cretaceous rocks of western Kansas

FIG. 1.—View along east side of road. North end.

faults of small displacement have been reported by Twenhofel,[1] Elias,[2] and also by Bass,[3] Russell,[4] and others. The rocks involved in the

[1] W. H. Twenhofel, "Significance of Some of the Surface Structures of Central and Western Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9, No. 7 (October, 1925), pp. 1061–70.

[2] M. K. Elias, "Origin of Cave-Ins in Wallace County, Kansas," *ibid.*, Vol. 14, No. 3 (March, 1930), pp. 316–20.

[3] N. W. Bass, *Geol. Survey Kansas Bull. 11* (1926), p. 44.

[4] William L. Russell, "Stratigraphy and Structure of the Smoky Hill Chalk in Western Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 6 (June, 1929), pp. 595–604.

displacements are chiefly the Niobrara chalk and the Greenhorn limestone. So far as the writer is aware no faults have been reported from the Comanche strata of Kansas. For that reason the data on a very remarkable display of deformed beds in Sec. 21, T. 16 S., R. 7 W., southeast of Kanopolis, Ellsworth County, are of interest.

FIG. 2.—View along east side of road. South end.

The section-line road was cut along the southwest side of Section 21 about the middle of the year 1935. Near the southwest corner of the section the topography slopes off rapidly toward Thompson Creek, resulting in high road-side cuts. In these cuts the flat Dakota sandstone, averaging several feet thick, overlies, by means of an angular unconformity, a considerable thickness of deformed Comanche

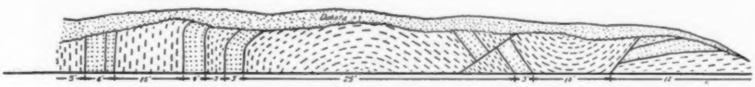

FIG. 3.—Drawing of deformed beds along east side of road.

clays and sandstones (Figs. 1–7). The Comanche rocks stand in vertical position on the east side of the road at one end of the exposure (Figs. 1 and 3). Farther south they are bent into a broad anticline and faulted syncline (Figs. 2 and 3).

On the west side of the road the same strata may be seen dipping steeply toward the north. Several faults with small displacement appear in the photographs (Figs. 4 and 5) and the illustrative drawing

(Fig. 6). The most significant structural feature appears near the south end of this exposure. There a pseudo-thrust fault may be seen (Fig. 7). Against it on the south the broken stratum may be seen with steep dip simulating the drag on the downthrown side.

FIG. 4.—View along west side of road. South end.

FIG. 5.—View along west side of road. North end.

The explanation for this structural anomaly in Kansas is not immediately apparent. Certainly no geologist would attribute it to a deep-seated cause, even though it does simulate Rocky Mountain deformation. The most reasonable cause lies in the assumption of a cave

in soluble rocks beneath the deformed area. Possible cavern collapse may have been occasioned by the dissolving away of salt layers which occur in the Wellington formation of the Permian.[5] In this part of the state the salt measures have a thickness of approximately 300 feet. They lie at a depth of about 650 feet below the surface. Inasmuch

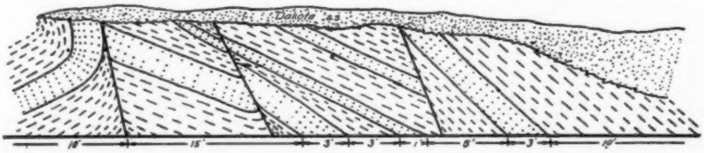

FIG. 6.—Drawing of beds along west side of road.

as they probably have caused the collapse of the upper Wellington strata farther east in Harvey County, it is not unreasonable to suppose that salt solution by circulating ground waters was also effective here.

An interesting side light on the whole situation is the fact that collapse of the underground cavern must have taken place after the

FIG. 7.—Close-up view of "thrust fault."

Comanche strata were laid down and before the Dakota was laid down over them, thus producing one of the finest pseudo-angular unconformities known.

[5] W. A. Ver Wiebe, "The Wellington Formation of Central Kansas," *Bull. Municipal University of Wichita*, Vol. 12, No. 5, *Univ. Studies Bull. 2* (May, 1937).

Acknowledgments.—This locality was first called to the writer's attention by Harry Boyd-Snee. The photographs were taken by Mr. Penny of the Laughlin-Simmons Well Elevation Service. The drawings were made by Dean McDaniel, geologist for the Shell Petroleum Company.

W. A. VER WIEBE

WICHITA, KANSAS
May 27, 1937

Pittsburgh Skyline from Mount Washington.

Plan to attend the mid-year meeting of the Association at Pittsburgh, October 14–16, 1937.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 21, NO. 7 (JULY, 1937), PP. 959-964

REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library and available to members and associates.

**The Geology of South-Western Ecuador*. By GEORGE SHEPPARD. Thomas Murby and Company, London (1937). 275 pp., 195 illus., maps, and diagrams. Outside dimensions, 5.75×8.75 inches. Specimen pages sent on request. Order from Association headquarters, Box 1852, Tulsa, Oklahoma. Price, clothbound, postage and import duty paid, $7.00.

At last it has been told, written in the King's English with distances in miles and elevations in feet. Dr. Sheppard has worked for 10 years in almost virgin territory and has packed the results of his labors into one small volume with hundreds of photographs, original sketches, and a geological map. Some of these data have appeared before in scientific journals. This is a source book which ranks with Bosworth's *Northwest Peru* and Liddle's *Geology of Venezuela*. Sheppard, like Bosworth and Liddle, at one time made geological explorations for petroleum.

The coastal shelf of Ecuador, 700 miles south of Panama, early attracted attention because of its brea pits and seepages. The coast of Peru adjacent to it on the south had similar occurrences, and it was natural to explore northward from the developing oil fields of that region.

Early explorers found a mud volcano east of Santa Elena which seeped oil. The immortal Cunningham Craig noted its similarity to those he had seen in Burma, Borneo, and Trinidad. He recommended a large concession and located a test hole near the volcano.

Joseph H. Sinclair studied this region in 1921 and was among the first to call attention to the highly contorted cherty shales of Eocene age into which the brea pits were dug. Many of his observations and photographs are included in the book.

The part of southwestern Ecuador described lies between the western base of the Andes and the Pacific. The rocks exposed range in age from Lower Tertiary to Recent. Great areas near the coast are covered by old raised sea-beach deposits called tablazos. Altogether a section of possibly 4,000 feet is exposed. The Eocene rocks of the Santa Elena Peninsula are given a great deal of attention because the author was at one time a resident of Ancon.

Since cherts and igneous rocks occur closely associated in the Santa Elena Peninsula, the chapter devoted to these rocks seems to be the very heart of the book and it is here that Sheppard has recorded his best work. The chapter on the Tertiary larger *Foraminifera* of southwest Ecuador was prepared by Dr. Wayland Vaughan. It includes beautiful illustrations of the larger *Foraminifera*, particularly *Discocyclina*, *Operculina*, and *Lepidocyclina*. Dr. Vaughan, in summing up his observations, says:

> Upper Eocene at Ancon is younger than the Lobitos beds of Peru, as reported by Henry Woods. The highest Eocene found appears to be equivalent to the Ocala limestone of Florida, showing that in late Eocene time Pacific and Atlantic sides had the same fauna, and suggests a connection of oceans.

The Guayaquil limestone was long called Cretaceous because Wolf and others claimed to have found *Inoceramus*. Vaughan, on the basis of *Fora-*

minifera found in samples collected by Sheppard, says this limestone is Upper Eocene. Sinclair collected rocks described as sandstone and siliceous limestone from the vicinity of Guayaquil which Coryell, on the basis of *Foraminifera*, none of which was similar to those found by Vaughan, called Cretaceous. It appears that the Guayaquil limestone is still open to discussion. It is the reviewer's guess that they have collected their specimens from different exposures and that further work will develop the fact that there are Cretaceous and Upper Eocene rocks in the vicinity of Guayaquil.

In addition to the oil developed at Ancon and farther west, the salt pans near Salinas, where the Ecuadorian Government has a monopoly on salt production, are of economic interest.

Another important Ecuadorian industry of this region which depends on geological factors influencing climate is the straw-hat industry of Monte Criste. Here the finest of the so-called Panama hats of commerce are produced.

Dr. Sheppard has given more than customary attention to geological processes which are active in tropical countries. This is best summed up by his statement in the chapter on sedimentation where he says, "tropical conditions with long periods of heat and short seasons of heavy rain favor rapid decomposition of rocks."

The whole book, with its well arranged photographs, sketches, and bibliography, gives the impression of a textbook. The reviewer's impression on completing the book is that the chapter on petroleum should have been expanded to include a map and description of the development at Ancon, together with the deep tests drilled on concessions in other parts of the area. Geological information from these deep holes would give a valuable third dimension which has not been adequately developed in the book.

The sketch shown as Figure 126 on page 190 and the cross section Figure 124 are the author's nearest approach to a regional setting for the area under discussion.

The Geology of South-Western Ecuador is a distinct contribution to South American geology and the author deserves great credit for his untiring efforts to assemble in one volume the detailed studies which he and other geologists have made in this region.

THERON WASSON

CHICAGO, ILLINOIS
June 3, 1937

RECENT PUBLICATIONS

AFRICA

Lexicòn de Stratigraphie. Vol. I: Africa. Compiled by a commission appointed by the 15th International Geological Congress. Thomas Murby and Company, London (1937). Price, 31s. 6 d.

Bibliographie géologique de l'Africa Centrale. Compiled under the direction of the African Geological Surveys' Association (a sub-committee of the 15th International Geological Congress, at Pretoria, 1929). Includes Equatorial French Africa, Belgian Congo, Angola, Kenya, Uganda, Tanganyika, Northern and Southern Rhodesia, and Nyasaland. 300 pp., 4,000 titles. May be ordered from Bur. d'Études Geol. et Min. Coloniales, 13, Rue de Bourgogne, Paris, or from Secrétariat de la Soc. Geol. Belgique, 7, Place du XX-Août, Liége (1937). Price: 60 francs français, or 80 francs belges.

ALASKA

"Geology of the Anthracite Ridge Coal District, Alaska," by G. A. Waring. *U. S. Geol. Survey Bull. 861* (1937). 57 pp., 14 pls., 3 figs. Price, $0.70.

ALGERIA-MOROCCO

*"Études géologiques sur les confins Algéro-Marocains du Sud" (Geological Studies in Southern Algeria and Morocco), by N. Menchikoff. *Bull. Soc. Geol. France* (28, rue Serpente, VI, Paris), Ser. 5, Vol. VI, Nos. 4–5 (1936), pp. 131–48; stratigraphic section.

ARGENTINA

*"Una interesante Filicínea fósil de la Patagonia" (An Interesting Fossil Fern of Patagonia), by Egidio Feruglio. *Bol. Inform. Petrol* (Buenos Aires) Vol. 14, No. 151 (March, 1937), pp. 5–20; 5 figs.

*"Contribución al conocimiento de la Estratigrafía del Liásico en el sur de la Provincia de Mendoza" (Contribution to Liassic Stratigraphy of Mendoza), by K. Egon Boehm. *Ibid.*, pp. 21–31; 2 maps.

AUSTRALIA

*"The Larger Foraminifera of the Lower Miocene of Victoria," by Irene Crespin. *Palaeontological Bull. 2* (1936). 15 pp., 2 pls. (27 figs.), map of Victoria showing foraminiferal localities. 8.5×10.75 inches. Dept. of Interior, Canberra, F. C. T., Australia.

CANADA

*"Age of the Exshaw Shale in the Canadian Rockies," by P. S. Warren. *Amer. Jour. Sci.* (New Haven, Connecticut), Vol. 33, No. 198 (June, 1937), pp. 454–57.

CHINA

Geology of China, by J. S. Lee. Physical geography, stratigraphy, tectonics, with discussion of wider problems of continental movement. Numerous maps, diagrams, and half-tones of fossils and land forms. Thomas Murby and Company, London (in press).

GENERAL

**Man in a Chemical World* (*The Service of Chemical Industry*), by A. Cressy Morrison. 292 pp., illus. Cloth. Charles Scribner's Sons, New York (1937). Price, $3.00.

**Oil and Petroleum Year Book, 1937*, compiled by Walter E. Skinner. "The international standard reference book on the oil industry of the world." 490 pp. Demy 8vo., bound in red cloth. Particulars about 735 companies (producers, refiners, transporters, dealers, oil finance companies). Published by Walter E. Skinner, 15, Dowgate Hill, Cannon Street, London, E.C.4. Price, 11s., net, post free abroad.

*"Sedimentation in Relation to Faulting," by Chester R. Longwell. *Bull. Geol. Soc. America* (New York), Vol. 48, No. 4 (April 1, 1937), pp. 433–42; 1 fig., 4 pls.

*"First Century of Progress in Cenozoic Marine Invertebrate Paleontology," by Gilbert D. Harris. *Ibid.*, pp. 443–62.

GEOPHYSICS

"Selection and Installation and Operation of Seismographs," H. E. McComb. *U. S. Coast and Geodetic Survey Spec. Pub. 206* (Washington, D. C., 1936). 42 pp. 37 figs., bibliog., 4 tables. Price , $0.10.

GERMANY AND POLAND

*"Vergleichende Studien über den deutschen und polnischen Erdölbergbau" (Comparative Studies of German and Polish Oil Fields and Operations), by T. von Bielski. *Petrol. Zeit.* (Vienna), Vol. 33, No. 18 (May 5, 1937), pp. 1–16; 23 figs.

ILLINOIS

"Geology and Oil and Gas Possibilities of Parts of Marion and Clay Counties, with a Discussion of the Central Portion of the Illinois Basin," by J. M. Weller and A. H. Bell. *Illinois Geol. Survey Bull. 40* (reprint, 1937). Urbana, Illinois. Price, $0.25.

IOWA

*"Geological Complex of Iowa Is Problem for Geophysicists," by W. G. Osborn. *Oil and Gas Jour.* (Tulsa, May 13, 1937), pp. 51–53; 2 maps.

KANSAS

*"The Wellington Formation of Central Kansas," by Walter A. Ver Wiebe. *Bull. Univ. Wichita* (Wichita, Kansas), Vol. 12, No. 5 (May, 1937). *University Studies Bull. 2.* 18 pp., 1 map.

KENTUCKY

"The Flora of the New Albany Shale. Part 2, The Calamopityeae and Their Relationships," by C. B. Read. *U. S. Geol. Survey Prof. Paper 186-E* (1937), pp. 81–104, Pls. 16–26, Fig. 1. Price, $0.15.

LOUISIANA

*"Lower Mississippi River Delta. Reports on the Geology of Plaquemines and St. Bernard Parishes." *Louisiana Geol. Survey Bull. 8* (dated at New Orleans, November 1, 1936; issued, 1937). 454 pp. Illus. 6×9 inches. Contains: "Physiography of Lower Mississippi River Delta," by Richard Joel Russell, pp. 3–199; "Salt Domes of Plaquemines and St. Bernard Parishes," by Henry V. Howe and James H. McGuirt, pp. 200–78; "Petrography of Two Mississippi River Sub-Deltas," by C. F. Dohm, pp. 339–96; "Igneous, Metamorphic and Sedimentary Pebbles from the Chandeleur Islands," by C. F. Dohm, pp. 397–402; "Some Notes on the Recent Mollusca from Plaquemines and St. Bernard Parishes," by Wade Hadley, Jr., pp. 403–06; *et cetera.*

MEXICO

*"Stratigraphy of Tampico Embayment of Mexico: A Review," by Charles Keyes. *Pan Amer. Geol.* (Geological Publishing Company, Des Moines, Iowa). Vol. 67, No. 5 (June, 1937), pp. 341–56; 2 maps.

*"Geology of the Middle Part of the Sierra de Parros, Coahuila, Mexico," by Ralph W. Imlay. *Bull. Geol. Soc. America* (New York), Vol. 48, No. 5 (May 1, 1937), pp. 589–630; 14 pls., 4 figs.

MICHIGAN

*"Possibility of Future Oil Production in Michigan," by Virgil R. D. Kirkham. *Oil and Gas Jour.* (Tulsa, May 13, 1937), pp. 45–46.

MISSOURI AND TEXAS

"The Correlation of the Upper Cambrian Sections of Missouri and Texas with the Section in the Upper Mississippi Valley," by Josiah Bridge. *U. S. Geol. Survey Prof. Paper 186-L* (1937), pp. 233–37. Price, $0.05.

OKLAHOMA

**Gorman's Petroleum Directory of Oklahoma, 1937*. 160 pp. "The purpose of the directory is to list all the companies and individuals in Oklahoma who are connected with the production of petroleum." Contents: general list of individuals and companies; royalty companies; drilling contractors; associations; pipe-line companies; abstracters (Oklahoma); filing fees; abstracters (Kansas). Published and for sale by B. R. Gorman, Box 395, Tulsa, Oklahoma. Price, prepaid, $1.00.

*"Methods for Catching Rotary Drill Samples in Oklahoma," by Paul Reed. *Oil and Gas Jour.* (Tulsa, June 10, 1937), pp. 42–48; 11 figs.

*"Microscopic Examination of Rotary Drill Cutting Samples," by L. H. Lukert. *Ibid.* (June 17, 1937), pp. 48–51; 7 figs.

PERSIA

*"Contribution a l'étude géologique de l'Anti-Elbouzr" (Geologic Study of the Anti-Elbourz), by A. Rivière. *Bull. Soc. Geol. France* (Paris), Ser. 5, Vol. VI, Nos. 4–5 (1936), pp. 277–98; 2 line drawings, 1 plate of fossils.

POLAND

*"Problems of Application of Seismic Reflection Methods in the Polish Eastern Carpathian Mountains in the Light of Present Investigations," by Z. Mitera. 21 pp., 10 figs. In Polish. English summary, 2 pp. "Application of geophysical methods of prospecting in the region of the Carpathian Mountains is rather difficult, due to the complexity of the geological structures encountered. . . . From several hundred records, obtained during the seismic work conducted by the Pionier Company in 1934 and 1935 in Poland, it was possible to tabulate the velocities of elastic waves for most typical Carpathian formations. . . . Therefore in conclusion it may be stated, that not the Carpathian Mountains but the Foreland offers most possibilities for successful application of reflection seismology." Reprinted from *Polish Geol. Soc. 12th Ann.* (Bohdanowicz 50th anniversary volume). Kraków (1936).

*"Geology of the Weglówka Area and Possibilities of New Oil Reserves," by Julian Obtulowicz. *Ibid.*, pp. 631–43; 6 figs. English summary, 2 pp. Points out possibilities of finding oil deposits in beds of Lower Cretaceous not only in the described region but in other tectonic elements of the West Carpathians.

*"Structural Conditions in the Boryslaw Sandstone at Boryslaw and in Western Tustanowice," by Józef Jakub Zielinski. *Ibid.*, pp. 644–57; 5 figs. English summary, 3 pp.

RUSSIA

*"The Mud Volcanoes of Kertch-Taman Region," by V. V. Beloussoff and L. A. Jarotsky. *Trans. Bur. Nat. Gas* (Moscow), *Fasc. 8* (1936). 154 pp., 25 line drawings in text, 18 photographs, 2 maps. Bibliography of 60 titles. In Russian. Summary in English, pp. 136–37. "Contains detailed description of 34 groups of mud volcanoes. . . . The maximum discharge of one volcano is 100 cubic meters daily. . . . The authors suppose that the gases may be in greater part the products of bacterial fermentation. They doubt their connection with gases from Mesozoic deposits on the northern slope of the Caucasus. . . . The waters of the volcanoes are strongly mineralized; are alkaline-saline; characterized by iodine and bromine; and are probably buried waters of sea muds. . . . Nearly all the volcanoes are confined to diapyric anticlinal cores."

*"Notes on the Correlation of Russian and Midcontinent Carboniferous and Permian Ammonite Zones," by F. B. Plummer. *Amer. Jour. Sci.* (New Haven), Vol. 33, No. 198 (June, 1937), pp. 462–69.

*"On the Carboniferous and Permian of the Southern Urals," by Carl O. Dunbar and A. K. Miller. *Ibid.*, pp. 470–72.

TEXAS AND NEW MEXICO

"Petroleum Engineering Study of the Big Spring Field and Other Fields in West Texas and Southeastern New Mexico," by Charles B. Carpenter and H. B. Hill. *U. S. Bur. Mines Rept. Investig. 3316* (November 1936). 223 pp., 40 illus. First edition exhausted; second edition now available from Chamber of Commerce, Midland, Texas, at $1.00 per copy.

UTAH-COLORADO

*"Structure of the Uinta Mountains," by J. Donald Forrester. *Bull. Geol. Soc. America* (New York), Vol. 48, No. 5 (May 1, 1937), pp. 631–66; 4 pls., 1 fig.

ASSOCIATION DIVISION OF PALEONTOLOGY AND MINERALOGY

**Journal of Paleontology* (Fort Worth, Texas), Vol. 11, No. 4 (June, 1937).

"Cretaceous Rudistids of Pinar del Rio Province, Cuba," by L. W. J. Vermunt.

"Pennsylvania Ostracoda from Sullivan County, Indiana," by Kenneth Armstrong Payne.

"The Tranquilla Shale (Upper Eocene) of Panama and Its Foraminiferal Fauna," by H. N. Coryell and John R. Embich.

"Stratigraphic Significance of Some Late Paleozoic Fenestrate Bryozoans," by Maxim K. Elias.

"A New Scorpion from the Pennsylvania *Walchia* Beds near Garnett, Kansas," by Maxim K. Elias.

"Evolutionary Tendencies in American Carboniferous Trilobites," by J. Marvin Weller.

"Foraminiferal Zonation of Certain Upper Cretaceous Clays of Texas," by Claude C. Albritton, Jr., and Fred B. Phleger, Jr.

"Large Oysters from the Gulf Coast Tertiary," by Henry V. Howe.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 21, NO. 7 (JULY, 1937), PP. 965-969

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to the Executive Committee, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

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MID-YEAR MEETING, PITTSBURGH, OCTOBER 14-16, 1937

The convention headquarters for the mid-year meeting of the Association is the William Penn Hotel.

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Outline of Events

OCT. 11, MON.	Field trip: from Pittsburgh through folded Appalachians of Maryland and West Virginia to New Market, Virginia (caverns)
OCT. 12, TUES.	Trip continued: up Shenandoah Valley to Lexington, Virginia, thence across mountains to Charleston, West Virginia Evening: banquet and Appalachian Geological Society symposium on oil and gas fields of West Virginia
OCT. 13, WED.	Trip continued: through historic fields of West Virginia to Pittsburgh
OCT. 14, THURS.	Local trips in and near Pittsburgh, in forenoon. Technical session in afternoon. Dinner in evening
OCT. 15, FRI.	Technical session in forenoon Trip to steel mill in afternoon Smoker in evening
OCT. 16, SAT.	Technical session in forenoon Carnegie Tech.-Notre Dame game in afternoon Field trip, following football game, to oil fields of northwestern Pennsylvania, including Drake well and Bradford field (flooding operations)
OCT. 17, SUN.	Field trip continued

TENTATIVE TECHNICAL PROGRAM

THURSDAY AFTERNOON

Address of welcome and response

GEORGE H. ASHLEY, Pennsylvania Geological Survey, "History of Development and the Geological Relationships of the Appalachian Fields"

L. L. NETTLETON, Gulf Research Laboratory, "Gravity, Magnetic and Geological Profile Across the Appalachian Mountains"

L. E. RANDALL, The Geophysical Company, Inc., "Seismograph Exploration in the Appalachian District"

FRIDAY MORNING

CHARLES R. FETTKE, Carnegie Institute of Technology, "The Oriskany in Pennsylvania"

ROBERT C. LAFFERTY, Owens-Libbey-Owens, "The Oriskany in West Virginia"

WILBUR H. STOUT, Geological Survey of Ohio, "Petroleum Geology of Eastern Ohio"

C. A. HARTNAGEL, New York State Museum, "The Medina and Trenton of Western New York"

SATURDAY MORNING

B. F. HAKE, Gulf Oil Corporation, "Geological Occurrence of Oil and Gas in Michigan"

THERON WASSON, Pure Oil Company, "Geological Occurrence of Oil and Gas in Illinois"

R. E. STOUDER, Louisville Gas and Electric Company, "The Chester Rocks of Meade, Hardin, and Breckinridge Counties, Kentucky"

NEWALL M. WILDER, Lexington, Kentucky, "Repressuring in Eastern Kentucky"

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 21, NO. 7 (JULY, 1937), PP. 970-973, 2 FIGS.

Memorial

LEON J. PEPPERBERG
(1883-1937)

The loss of so cherished a friend as Leon J. Pepperberg, by his sudden death on May 12, 1937, is but feebly compensated for by the tender memories of a friendship extending over a period of nearly 20 years.

Leon J. Pepperberg was born January 20, 1883, at Plattsmouth, Nebraska, the son of Julius and Alice Pepperberg. He obtained his bachelor's degree from the University of Nebraska in 1905, continued as a fellow in the department of geology for the ensuing year, and in 1908 received his M.A. degree from the same institution. The following year he married Rachel F. Carns, who, with one son, Leon E., survives.

Mr. Pepperberg's professional career was a varied one, beginning with three years as an assistant geologist on the Nebraska Geological Survey, 1903-1906; during the period from 1906 to 1910, he was a member of the Fuel Division of the United States Geological Survey; he resigned the latter position to become geologist for the Southern Pacific Railroad for the period, 1910-1912. He then established himself as consulting geologist and engineer at San Francisco, California, and, during a 4-year period, specialized in the valuation of oil and gas properties in California, Wyoming, Oklahoma, Texas, Old Mexico, and Canada. For 2 years of this time, he was also a director of the firm of Smith-Emory and Company, chemical engineers. From 1917 to 1919, he was geologist and general manager for C. J. Wrightsman, with various oil properties in Kansas, Oklahoma, Texas, and Wyoming. In 1919, he moved to Dallas as consulting geologist and engineer, where he participated actively in the early development of Stephens and Eastland counties, the Laredo district, and the Mexia fault zone. He is generally credited with the discovery of the Ivan and Nigger Creek pools of Texas and the southern extension of the El Dorado pool of Arkansas. He also served as consulting geologist during 1919-1920 for Col. George W. Goethals, in connection with the Lake Dallas Project. In 1928, he became consulting geologist for the Columbia Engineering and Management Corporation (Columbia Gas and Electric Corporation) and had an active part in the development of north-central Pennsylvania and southern New York. At the close of his connection with the Columbia Corporation, in 1931, he returned to Dallas, which remained his home.

Mr. Pepperberg's principal publications included: *U. S. Geological Survey Bulletins 280J, 381A, 430C, and 471E*; "Nigger Creek Oil Field, Limestone County, Texas," *Structure of Typical American Oil Fields*, Vol. I (Amer. Assoc. Petrol. Geol., 1929); "Basic Data for Oil and Gas Wells" (joint author Eugene A. Stephenson), *Petroleum Development and Technology* (A.I.M.E., 1934), pp. 84-94; together with numerous short articles in *Mining & Science Press*, *Western Engineering*, *Oil Weekly*, and *National Petroleum News*.

He was a member of the following technical societies: American Association of Petroleum Geologists, American Institute of Mining and Metallurgical Engineers, American Petroleum Institute, Geological Society of Washington, Society of Economic Geologists, Dallas Petroleum Geologists, Ohio Academy of Science. His clubs were: University, Masons.

The outstanding characteristics of our deceased friend were his vision, his unswerving integrity, and his indefatigable perseverance in the search for sound conclusions in whatever field of endeavor he pursued (and these fields were numerous and broad.) The writer has known of many cases in which Leon Pepperberg was approached by various clients to accept assign-

Courtesy of Roy Lee Jackson

LEON J. PEPPERBERG

ments of work which meant considerable profit, but he never failed to inform the client that, even though the conclusions which he might draw from his investigations would be contrary to the interests of the client, he would steadfastly adhere to those conclusions. Keen of wit, and with a delightful sense of humor, he had an optimistic outlook on life which was almost contagious; he regarded his civic and scientific duties as sacred trusts which no adversity could shake. Deeper acquaintance brought only greater admiration and re-

spect for him, both professionally and personally. Our sympathies for his family are hereby expressed; we, too, loved him.

EUGENE A. STEPHENSON

ROLLA, MISSOURI
June 7, 1937

HERBERT GEORGE OFFICER
(1889–1937)

Herbert George Officer, a successful petroleum geologist and executive of Tulsa, Oklahoma, died May 18, 1937, in Monterey, California. His death was due to pneumonia after a short illness.

HERBERT GEORGE OFFICER

Bert Officer was born in Buttersville, Michigan, on May 28, 1889. He was graduated from the University of South Carolina in 1911, at which time he

received a B.S. and an M.A. degree. He attended Columbia School of Mines from 1911 to 1913, receiving an E.M. degree from that institution.

Mr. Officer followed mining engineering for a number of years thereafter. Immediately after graduation he was engaged as engineer, and later became manager, of a famous group of silver mines in Huantajaya, Chile, where he remained until 1915. While in this position Mr. Officer surveyed for the first time many miles of undergound workings originally dug by the Inca Indians and later expanded by the Spaniards.

Mr. Officer was engineer and geologist for the Andes Exploration Company from 1916 to 1918, and chief geologist for the Santiago Mining Company from 1919 to 1921.

In 1922 he entered the oil business, working as a geologist for the Amerada Petroleum Corporation and later with the Twin State Oil Company and the Sinclair Oil Company. In 1926 Bert permanently joined the Amerada staff as a junior executive in the land department, and a few years later became head of that department.

His work with the Amerada was rapidly increased in its scope, and he was chiefly responsible for the extensive land operations of that company. Mr. Officer became widely known throughout the entire Mid-Continent area. Due to his early training he materially assisted in the interpretation of geological data and the evaluation of geological and geophysical prospects. In this work he was invaluable to the Amerada. His career was a shining example of successful executive direction based on technical knowledge. His outstanding qualities as a man and the high standard which he set for himself in the field of human relationships won him a host of friends, and his loss will be keenly felt throughout the oil country and the mining industry generally.

Besides his widow, Helen Bugbee Officer, he left a daughter Helen, aged 16, and two sons, Herbert, Jr., aged 15, and Tommy, aged 9.

JOHN M. LOVEJOY

NEW YORK, N. Y.
May 28, 1937

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 21, NO. 7 (JULY, 1937), PP. 974-976

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

The official delegates appointed by President Roosevelt to represent the United States at the seventeenth International Geological Congress at Moscow, July 20–29, are: PHILIP S. SMITH, WALTER H. BUCHER, ERMINE C. CASE, GEORGE E. CONDRA, GEORGE B. CRESSEY, CARL O. DUNBAR, JULIA GARDNER, JEWELL J. GLASS, MARCUS I. GOLDMAN, EDWARD P. HENDERSON, LOY W. HENDERSON, BENJAMIN F. HOWELL, ARVILLE I. LEVORSEN, JOHN P. MARBLE, ARTHUR K. MILLER, RAYMOND C. MOORE, NORMAN D. NEWELL, JAMES S. WILLIAMS, WILLIAM E. WRATHER.

J. D. WHEELER, petroleum engineer with the Ohio Oil Company, has moved from Tulsa to Houston. His address is Box 3128, Houston, Texas.

HUGO R. KAMB, recently with the Louisiana Oil Refining Corporation, has accepted the position of district geologist with the Arkansas Natural Gas Corporation for North Louisiana, South Arkansas, and Mississippi. His address is Box 1734, Shreveport, Louisiana.

W. I. INGHAM is employed by the Mid-Continent Petroleum Corporation in Kansas.

WALLACE E. PRATT, vice-president of the Humble Oil and Refining Company, Houston, Texas, since 1933, has been elected to the board of directors of the Standard Oil Company of New Jersey and to the executive committee of the company. His address is 30 Rockefeller Plaza, New York City.

L. P. TEAS has been appointed chief geologist for the Humble Oil and Refining Company, Houston, Texas.

SAMUEL C. JOHNSON, who graduated from Columbia University, New York, in 1936, is employed by the Seismograph Service Corporation of Tulsa, Oklahoma.

The African Geological Surveys' Association is composed of the geological surveys of French West Africa, Gold Coast, Nigeria, Cameroun, French Equatorial Africa, Angola, Belgian Congo, Kenya and Uganda, Tanganyika, Nyasaland, Northern Rhodesia, and Southern Rhodesia. The secretaryship of the association is at the Bureau d'Études géologiques et minières coloniales, F. Blondel, director, 13, Rue de Bourgogne, Paris, 7e. An international geological map of Africa is in preparation.

The council of the Geological Society of America has nominated the following officers: president, ARTHUR L. DAY, Washington, D. C.; past-president, CHARLES PALACHE, Cambridge, Massachusetts; vice-presidents, T. WAYLAND VAUGHAN, Washington, D. C., WARREN J. MEAD, Cambridge, Massachusetts, JOSEPH A. CUSHMAN, Sharon, Massachusetts, N. L. BOWEN, Washington, D. C.; secretary, CHARLES P. BERKEY, New York City; treasurer, EDWARD B. MATHEWS, Baltimore, Maryland. Nominations for additional councilors are: MORLEY E. WILSON, Ottawa, Canada; JOHN B.

REESIDE, JR., Washington, D. C.; HENRY A. BUEHLER, Rolla, Missouri; ELIAS H. SELLARDS, Austin, Texas.

NOEL EVANS has changed his address from Oklahoma City, Oklahoma, to Tide Water Oil Company, Esperson Building, Houston, Texas.

EUGENE A. STEPHENSON, professor of petroleum engineering at the Missouri School of Mines at Rolla since 1930, has been appointed to take charge of petroleum engineering at the University of Kansas at Lawrence.

A. ROGER DENISON has been promoted from the position of district geologist for the Amerada Petroleum Corporation at Fort Worth, Texas, to the new position of chief geologist at Tulsa, Oklahoma. MRS. DOLLIE RADLER HALL is administrative geologist at Tulsa. J. F. HOSTERMAN is district geologist at Fort Worth.

D. D. HENINGER, geologist with The Ohio Oil Company, formerly at Houston, Texas, is now with the same company at San Antonio, Texas.

DONALD E. FUELLHART, formerly an engineer with Brokaw, Dixon, Garner and McKee, has resigned to become conservation engineer in the Louisiana Department of Conservation. He may be addressed at Natchitoches.

GLEN B. GARIEPY has been appointed chief geologist for the Ohio Oil Company in Los Angeles. THOMAS BOWLES will take over Mr. Gariepy's former duties as geologist in Bakersfield.

BERNARD H. LASKY, geologist, is now located in the Sterling Building, Houston, Texas.

KENNETH M. WILLSON has changed his address from Shreveport, Louisiana, to 1104 Cosden Building, Tulsa, Oklahoma.

The South Texas Geological Society has more than 200 members and the number is increasing according to HARRY H. NOWLAN, president, 833 Milam Building, San Antonio. The May meeting was held at Corpus Christi under the chairmanship of W. A. MALEY, vice-president. Chief chemist DAVIES, of the Southern Alkali Corporation, read the paper of the evening, after which there was a dinner dance on the deck of the Plaza Hotel. The annual picnic and baseball game, attended by 250 people, were held at New Braunfels under the chairmanship of PHILIP S. SHOENECK. The June meeting was held at the Petroleum Club, San Antonio, June 21.

The newly elected officers of the Tulsa Stratigraphic Society are as follows: president, R. V. HOLLINGSWORTH, Shell Petroleum Corporation; vice-president, L. H. LUKERT, The Texas Company; secretary-treasurer, E. D. CAHILL, Skelly Oil Company.

WILLIAM NORVAL BALLARD resigned June 15 from Phillips Petroleum Company, Bartlesville, Oklahoma, to become associated with A. I. LEVORSEN and FRED H. MOSER of Tulsa.

MARK C. MALAMPHY, formerly with the Instituto Geologicao e Mineralogico Do Brazil, Praia Vermelha, Rio de Janeiro, is now a consulting geophysicist in Cumberland, Maryland. His address is 304 Park Street.

K. WASHINGTON GRAY, who has been with the Commonwealth Oil Refineries, Ltd., Melbourne, Australia, returned to England June 1. He may be addressed at the Anglo-Iranian Oil Company, Ltd., Brittanic House, Finsbury Circus, London, E.C. 2.

ROBERT CECIL LANE, formerly of Waco, Texas, is now doing geological work in New York and Pennsylvania for Godfrey L. Cabot, Inc., 516 Exchange National Bank Building, Olean, New York.

REAGAN TUCKER has resigned as geologist with the Kenco Corporation to become geologist for the Buckingham Oil Company with headquarters at Corpus Christi, Texas.

JOHN F. DODGE, professor of petroleum engineering at the University of Southern California, is on an extended trip around the world. Prior to returning next February, he will spend several months of study in the oil fields of Borneo, Sumatra, and the interior of India. A study of foreign drilling methods will also be made in China and Japan.

LOUIS N. WATERFALL has been appointed assistant chief geologist of the Union Oil Company, and will be in charge of geophysical work. He will also assist the chief geologist in the administrative duties of that department.

M. B. ARICK, recently with the Humble Oil and Refining Company at Midland, Texas, is now senior geologist in charge of field work for the Lago Petroleum Company at Maracaibo, Venezuela.

A. P. LOSKAMP, of the Barnsdall Oil Company at Midland, Texas, has succeeded M. B. ARICK as vice-president of the West Texas Geological Society.

FREDERIC H. LAHEE has been appointed to membership in the National Research Council as representative of the Association in the Division of Geology and Geography during the next 3 years. CHESTER A. LONGWELL is chairman of the Division.

CORNELIA CAMERON, recently instructor in geology at the Eldorado, Kansas, Junior College, has accepted a position with the Empire Oil and Refining Company at Wichita, Kansas.

The Kansas Geological Society announces its eleventh annual field conference to be held in southeastern Kansas and northeastern Oklahoma, September 3–6. The conference will be primarily a continuation of previous conference studies of the Pennsylvanian rocks of Kansas and adjoining states. R. C. MOORE, State geologist of Kansas, director of the conference, will be assisted by K. K. LANDES, assistant State geologist. ROBERT H. DOTT, director of the Oklahoma Geological Survey, and J. M. JEWETT, University of Wichita, will aid in the preliminary field work and the conduct of the conference. A registration fee, not to exceed $8, including the price of the guide book, will be charged to help defray the expenses of the conference. Extra guide books may be purchased for not more than $5 each. JAMES I. DANIELS, 820 Union National Bank Building, Wichita, is president, and VIRGIL B. COLE, 1107 Union National Bank Building, is secretary-treasurer of the Kansas Geological Society.

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Luncheon meetings, first and third Mondays of each month, 6:15 P.M., Auditorium Hotel.

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Regular Meetings: 7:30 P.M., Allis Hotel, first Tuesday of each month. Visitors cordially welcomed.

The Society sponsors the Kansas Well Log Bureau which is located at 412 Union National Bank Building.

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Arkansas Fuel Oil Company

Meets the first Friday of every month, Civil Courts Room, Caddo Parish Court House. Luncheon every Friday noon, Caddo Hotel.

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Meetings: Second Monday, each month, 8:00 P.M., Commerce Exchange Building. Luncheons: Every Monday, 12:15 P.M., Commerce Exchange Building.

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The Texas Company

Meets the fourth Monday of each month at 8:00 P.M., at the Aldridge Hotel. Visiting geologists welcome.

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Gulf Oil Corporation

Meetings: First and third Mondays, each month, from October to May, inclusive, at 8:00 P.M., fourth floor, Tulsa Building. Luncheons: Every Thursday, fourth floor, Tulsa Building.